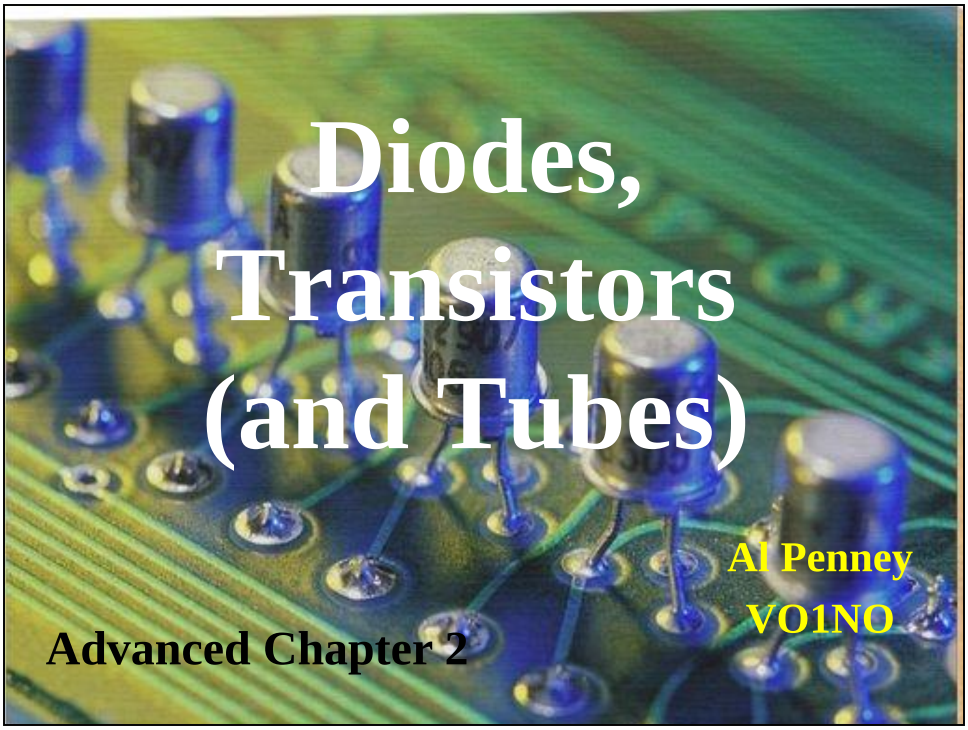
Diodes, Transistors (and Tubes)
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Advanced Chapter 2

Basic Atomic Structure

- **Everything** in the Universe is made up of **Atoms.**
- To explain the behavior of atoms, we can **visualize atoms as solar systems.**
- The center, or **Nucleus,** of the atom is composed of **Protons** and **Neutrons.**
- In **orbit** around the nucleus are one or more **Electrons.**

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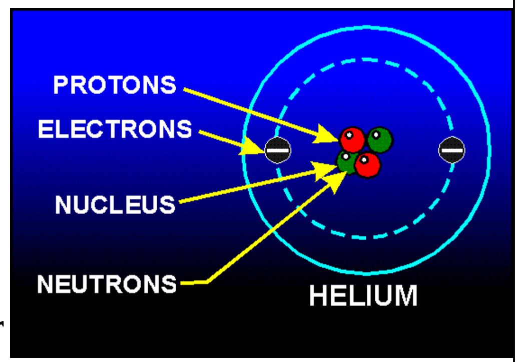
Atomic Structure

- **Protons** have a **Positive** charge.
- **Neutrons** are electrically **neutral.**
- **Electrons** have a **Negative** charge.
- Protons and Neutrons are about **1800 times heavier** than Electrons.



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Valence Electrons

- Electrons are arranged in several **discrete orbits,** with a **maximum** number per orbit.
  - 1st 2 electrons
  - 2nd 8 electrons
  - 3rd 18 electrons
  - 4th 32 electrons
  - 5th 50 electrons
- The electrons in the **outermost orbit** are called the **Valence Electrons.**

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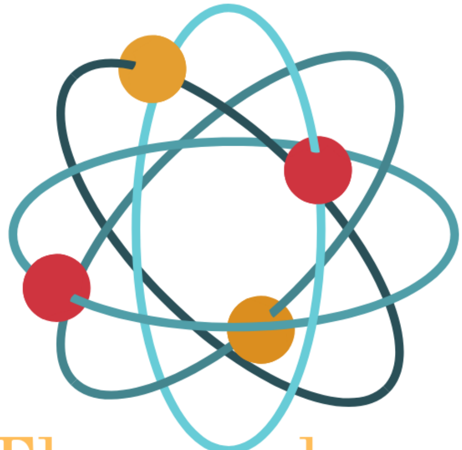
Never trust an atom.



They make up everything.

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Atomic Bonds

- **Valence electrons** enable atoms to **bond** with other atoms.
- **Ionic Bond** – attraction based on oppositely charged ions eg: NaCl (salt).
- **Metallic Bond** – electrons are **loosely bound** and can **move freely** among the atoms eg: metals.
- **Covalent Bond** – each atom **shares its electrons** with other atoms, forming an **orderly network** called a **lattice structure.**

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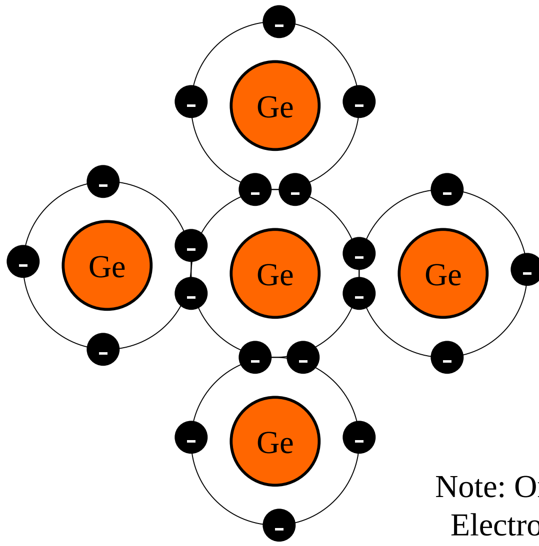
Germanium Covalent Bond



Note: Only Valence Electrons shown.

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Conductivity of Materials

- **Conductivity** is a measure of a material's **ability to conduct electricity.**
- Good **Conductors** have a large number of **free electrons.**
- **Insulators** have atomic structures where the **electrons are tightly bound,** and **cannot** be used to **conduct electricity.**

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Conductors

- **Metals** are good conductors.
- They include:
  - **Copper**
  - **Aluminum**
  - **Silver**
  - **Gold**

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Insulators

- **Insulators** include:
  - **Plastics**
  - **Rubber**
  - **Dry Wood**
  - **Porcelain**
  - **Dry Air**

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Semiconductors

- **Between** Conductors and Insulators is another category of materials classified as **Semiconductors.**
- They are **neither good conductors, nor good insulators.**
- Semiconductors include **Silicon**, **Germanium** and **Gallium-Arsenide.**

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Gallium Arsenide GaAs

- A compound of the elements Gallium and Arsenic.
- Forms a semiconductor used in the manufacture of:
  - microwave frequency integrated circuits;
  - monolithic microwave integrated circuits (MMICs); and
  - infrared light-emitting and laser diodes, solar cells etc.
- Can function at **frequencies greater than 250 GHz**.
- Less sensitive to heat, produces less electrical noise.
- **Preferred over silicon/germanium for microwave devices.**

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Doping Semiconductors

- Ordinarily, semiconductors are poor conductors.
- When certain **impurities** are added however, their **conductivity improves.**
- The process of **adding impurities** is called **Doping.**
- Depending on the dopant, an **extra electron**, or a **Hole** (“missing” electron) can be added to the lattice structure.

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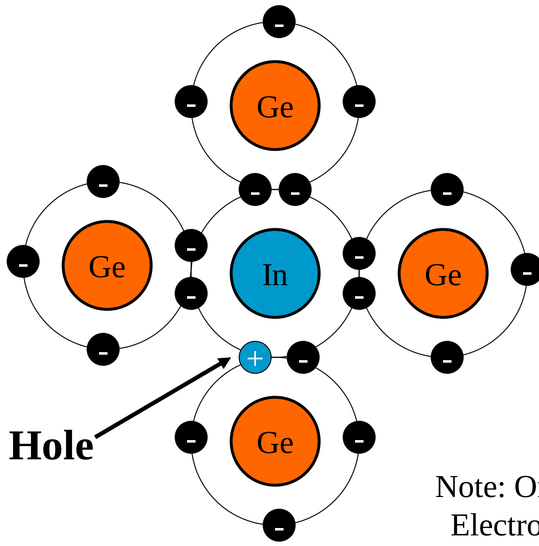
Germanium with Indium Doping



Note: Only Valence Electrons shown.

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P-Type material

- The **absence of an electron** creates a **“hole”.**
- The **motion of this hole (Majority Carrier)** will support the **conduction of electricity,** as electrons are displaced to fill the hole.
- Because the conduction of electricity is primarily supported by **positive holes,** substances like this are called **P-Type material.**
- There are still some free electrons available for conducting electricity **(Minority Carrier).**

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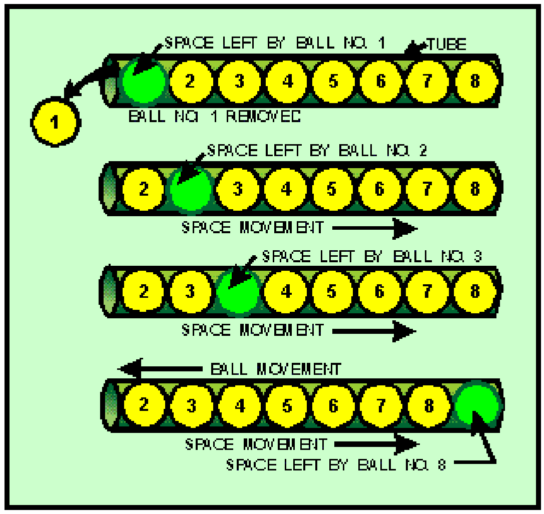
Conduction with Holes



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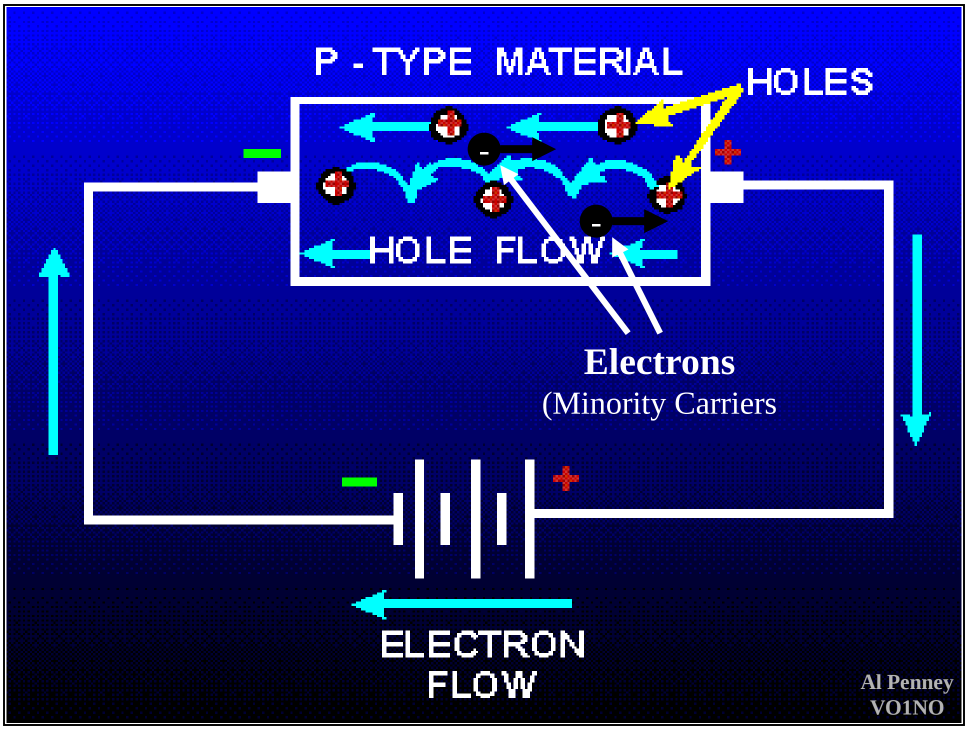
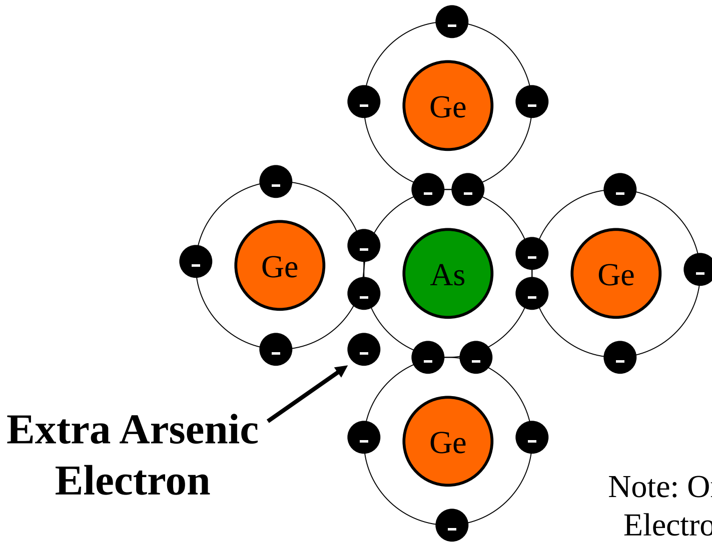


Current Flow in the P-Type Material

Current flow through the P-type material is illustrated in figure 1-16. Conduction in the P material is by positive holes, instead of negative electrons. A hole moves from the positive terminal of the P material to the negative terminal. Electrons from the external circuit enter the negative terminal of the material and fill holes in the vicinity of this terminal. At the positive terminal, electrons are removed from the covalent bonds, thus creating new holes. This process continues as the steady stream of holes (hole current) moves toward the negative terminal.

Notice in both N-type and P-type materials, current flow in the external circuit consists of electrons moving out of the negative terminal of the battery and into the positive terminal of the battery. Hole flow, on the other hand, only exists within the material itself.

Germanium with Arsenic Doping



Note: Only Valence Electrons shown.

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N-Type Material

- Because there are **“extra” electrons** that are not part of the covalent bonds, conduction of electricity is primarily through the **movement of these electrons (Majority Carriers).**
- Because **electrons** have a **negative charge,** these substances are called **N-Type**.
- There are still some holes available in N-Type material **(Minority Carriers).**

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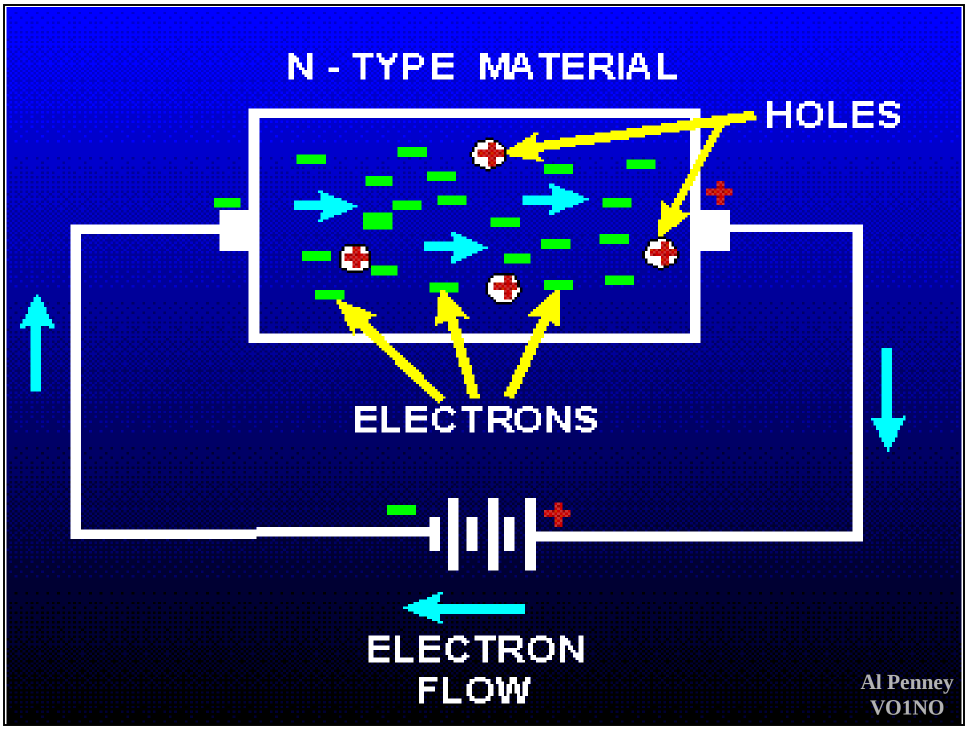

Current Flow in the N-Type Material

Conduction in the N-type semiconductor, or crystal, is similar to conduction in a copper wire. That is, with voltage applied across the material, electrons will move through the crystal just as current would flow in a copper wire. This is shown in figure 1-15. The positive potential of the battery will attract the free electrons in the crystal. These electrons will leave the crystal and flow into the positive terminal of the battery. As an electron leaves the crystal, an electron from the negative terminal of the battery will enter the crystal, thus completing the current path. Therefore, the majority current carriers in the N-type material (electrons) are repelled by the negative side of the battery and move through the crystal toward the positive side of the battery.

P-N Junction

- When P-type and N-type material are placed together, **electrons** and **holes** near the boundary **recombine.**
- This creates a region with **negatively charged atoms in the P-type** material, and **positively charged atoms in the N-type material.**
- This is called the **Depletion Zone,** because there is a lack of holes and electrons.
- It is very thin – approximately 0.01 mm thick.

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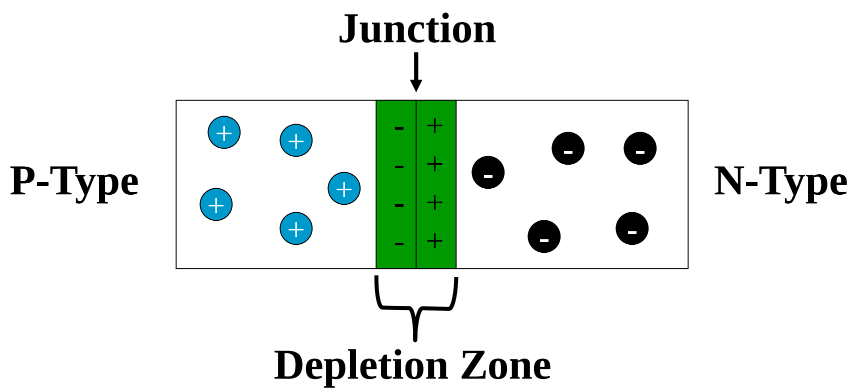
Junction Barrier



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Junction Barrier

- It is **not possible** for **electrons** to **migrate** from the N-type material into the P-type material because they are **repelled** by the **negatively charged atoms** (called **Ions**) in the **Depletion Zone.**
- For this reason, the electric field created by the ions is called the **Junction Barrier.**

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Junction Barrier Potential

- This electric field is small:
  - ~ 0.3 volts for germanium
  - ~ 0.7 volts for silicon
- Once established, **no further current flows** across the junction.
- For a current to flow, we must **overcome the barrier potential.**

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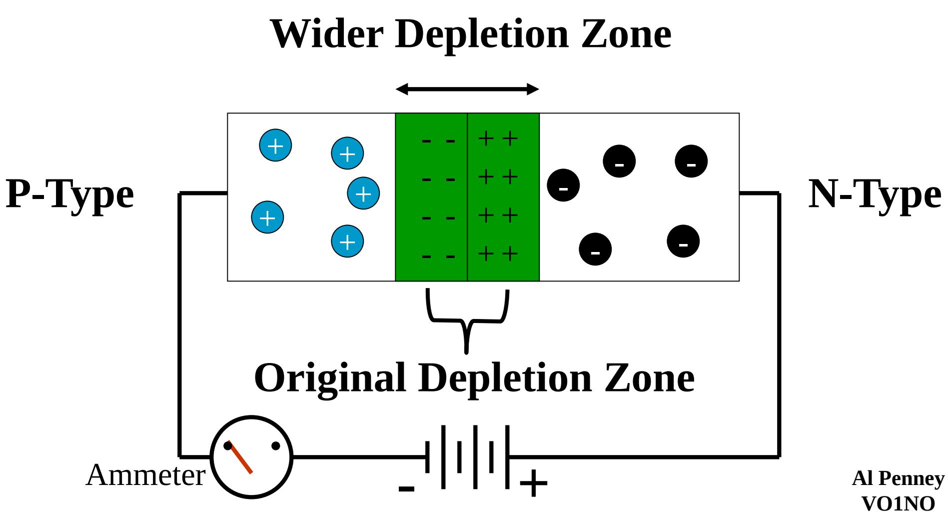
After joining p-type and n-type semiconductors, electrons from the n region near the p–n interface tend to diffuse into the p region. As electrons diffuse, they leave positively charged ions (donors) in the n region. Likewise, holes from the p-type region near the p–n interface begin to diffuse into the n-type region, leaving fixed ions (acceptors) with negative charge. The regions nearby the p–n interfaces lose their neutrality and become charged, forming the space charge region or depletion layer.

The electric field created by the space charge region opposes the diffusion process for both electrons and holes. There are two concurrent phenomena: the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion. The carrier concentration profile at equilibrium is shown in figure A with blue and red lines. Also shown are the two counterbalancing phenomena that establish equilibrium.

Reverse-Biased Junction Barrier



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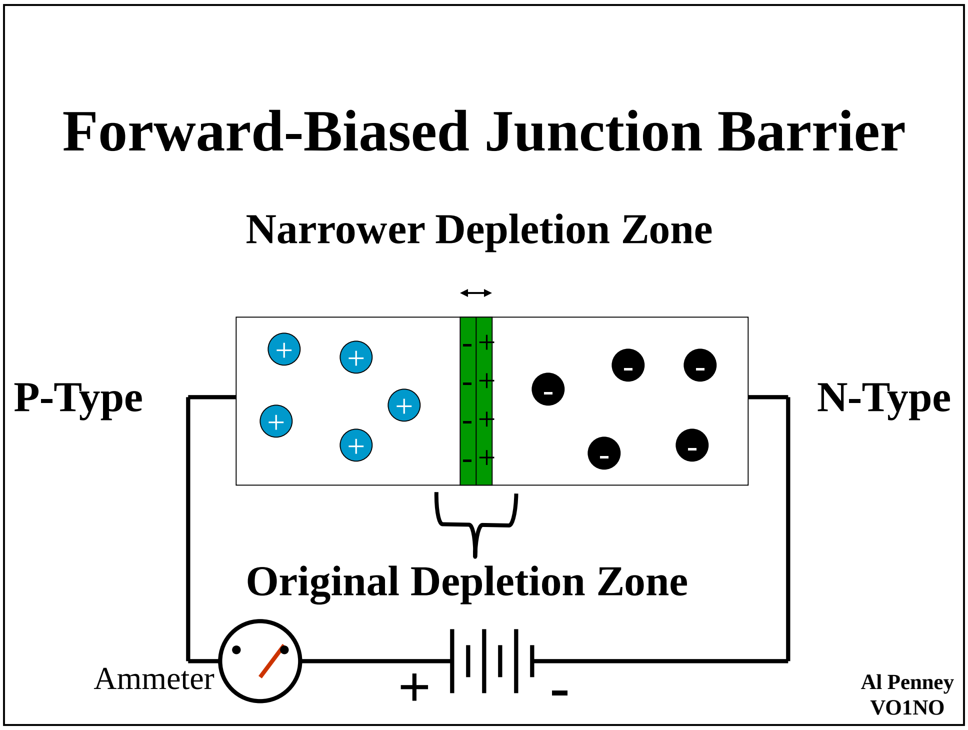
Forward-Biased Junction Barrier
Narrower Depletion Zone
P-Type
N-Type
Original Depletion Zone
Ammeter
+
-
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Diodes

- A PN junction allows current to flow in **one direction only**.
- This forms a diode.
- Used to rectify AC and demodulate AM transmissions among other things.

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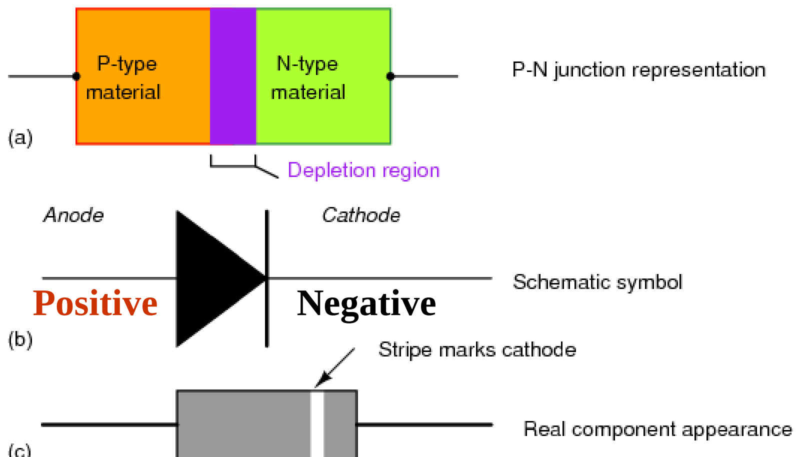
Diode Symbol



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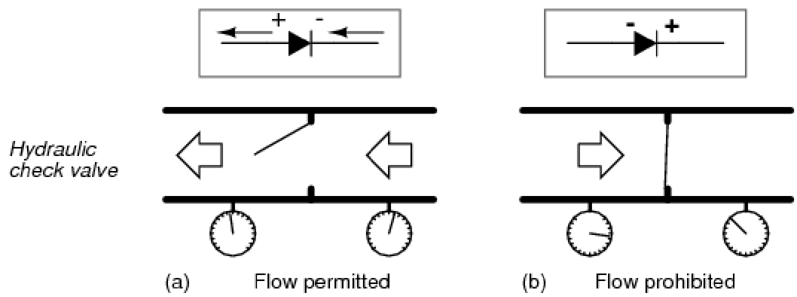
Valve Equivalent of Diodes



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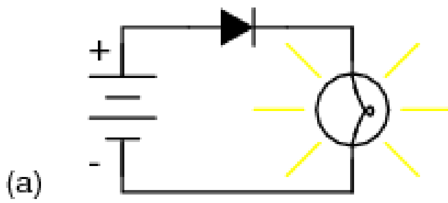
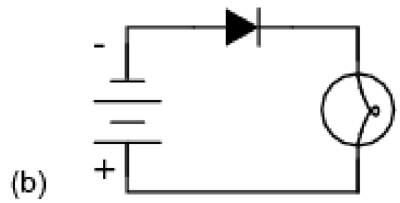
Biasing





Forward Biased **Reverse Biased**

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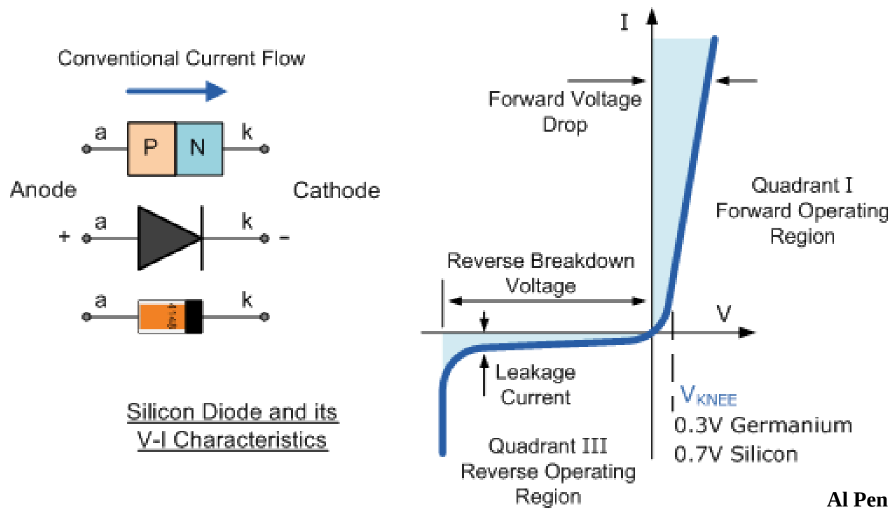
Diode Voltages



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The arrow always points in the direction of conventional current flow through the diode meaning that the diode will only conduct if a positive supply is connected to the Anode, (a) terminal and a negative supply is connected to the Cathode (k) terminal thus only allowing current to flow through it in one direction only, acting more like a one way electrical valve, (Forward Biased Condition).

However, we know from the previous tutorial that if we connect the external energy source in the other direction the diode will block any current flowing through it and instead will act like an open switch, (Reversed Biased Condition)

Diode Parameters

- **Peak Inverse Voltage (PIV)** - maximum allowable **Reverse** operating voltage that can be applied across the diode without avalanche or **Zener** breakdown and damage occurring to the device.
- Always give lots of safety margin!
- **Key parameter.**

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Peak Inverse Voltage

The **Peak Inverse Voltage** (PIV) or *Maximum Reverse Voltage* ($V_{R(max)}$), is the maximum allowable **Reverse** operating voltage that can be applied across the diode without reverse breakdown and damage occurring to the device. This rating therefore, is usually less than the "avalanche breakdown" level on the reverse bias characteristic curve. Typical values of $V_{R(max)}$ range from a few volts to thousands of volts and must be considered when replacing a diode.

The peak inverse voltage is an important parameter and is mainly used for rectifying diodes in AC rectifier circuits with reference to the amplitude of the voltage were the sinusoidal waveform changes from a positive to a negative value on each and every cycle.

Diode Parameters

- **If_{max}** – Maximum forward current that can flow continuously without damage. Exceeding If_{max} will cause permanent damage. **Key parameter.**
- **Forward Voltage V_F** – Voltage drop across diode at maximum rated current. Peak output voltage in rectifier circuit will be peak input voltage minus this Forward Voltage.

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Maximum Forward Current

The **Maximum Forward Current** ($I_{F(max)}$) is as its name implies the *maximum forward current* allowed to flow through the device. When the diode is conducting in the forward bias condition, it has a very small "ON" resistance across the PN junction and therefore, power is dissipated across this junction (Ohm´s Law) in the form of heat.

Then, exceeding its ($I_{F(max)}$) value will cause more heat to be generated across the junction and the diode will fail due to thermal overload, usually with destructive consequences. When operating diodes around their maximum current ratings it is always best to provide additional cooling to dissipate the heat produced by the diode.

For example, our small 1N4148 signal diode has a maximum current rating of about 150mA with a power dissipation of 500mW at 25^{o}C. Then a resistor must be used in series with the diode to limit the forward current, ($I_{F(max)}$) through it to below this value.

Diode Parameters

- **Maximum Power Dissipation P_D** – Related to amount of heat diode can dissipate without danger of overheating junction. Depends on installation environment.
- **Junction Capacitance** – Capacitance formed by PN junction under reverse bias. Can affect the circuit in which diode is installed. Point contact diodes have low values of capacitance.

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Total Power Dissipation

Signal diodes have a **Total Power Dissipation**, ($P_{D(max)}$) rating. This rating is the maximum possible power dissipation of the diode when it is forward biased (conducting). When current flows through the signal diode the biasing of the PN junction is not perfect and offers some resistance to the flow of current resulting in power being dissipated (lost) in the diode in the form of heat.

As small signal diodes are non-linear devices the resistance of the PN junction is not constant, it is a dynamic property then we cannot use Ohms Law to define the power in terms of current and resistance or voltage and resistance as we can for resistors. Then to find the power that will be dissipated by the diode we must multiply the voltage drop across it times the current flowing through it: $P_D = V*I$

Maximum Operating Temperature

The **Maximum Operating Temperature** actually relates to the *Junction Temperature* (T_J) of the diode and is related to maximum power dissipation. It is the maximum temperature allowable before the structure of the diode deteriorates and is expressed in units of degrees centigrade per Watt, ($^oC/W$).

This value is linked closely to the maximum forward current of the device so that at this value the temperature of the junction is not exceeded. However, the maximum forward current will also depend upon the ambient temperature in which the device is operating so the maximum forward current is usually quoted for two or more ambient temperature values such as 25^{o}C or 70^{o}C.

Junction capacitance is **the capacitance which forms in a PN junction diode under reverse bias**. In a normal capacitor, the two parallel conducting plates are electrodes which allow the conduction. Whereas, the medium between two parallel conducting plates is purely insulating dielectric material which does not allow conduction.

When a voltage or potential difference is applied across a capacitor the charges accumulates at the electrodes. The voltage will not move through the dielectric. But the dielectric medium will allow an electric field to flow through it when huge number of charges accumulates at the electrodes. However, the electrodes are able to store electric charge. This ability of storing electric charge is known as capacitance.

Diode Categories

- Two main categories of semiconductor diodes:
  - **PN Junction**; and
  - **Point Contact**.

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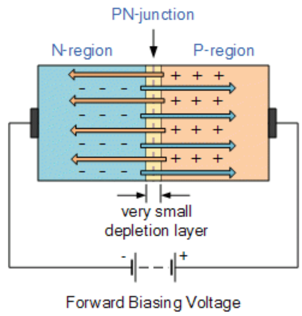
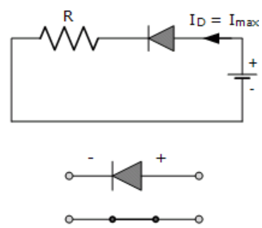
Junction Diode

- P and N type semiconductors fused to form potential barrier voltage at junction.





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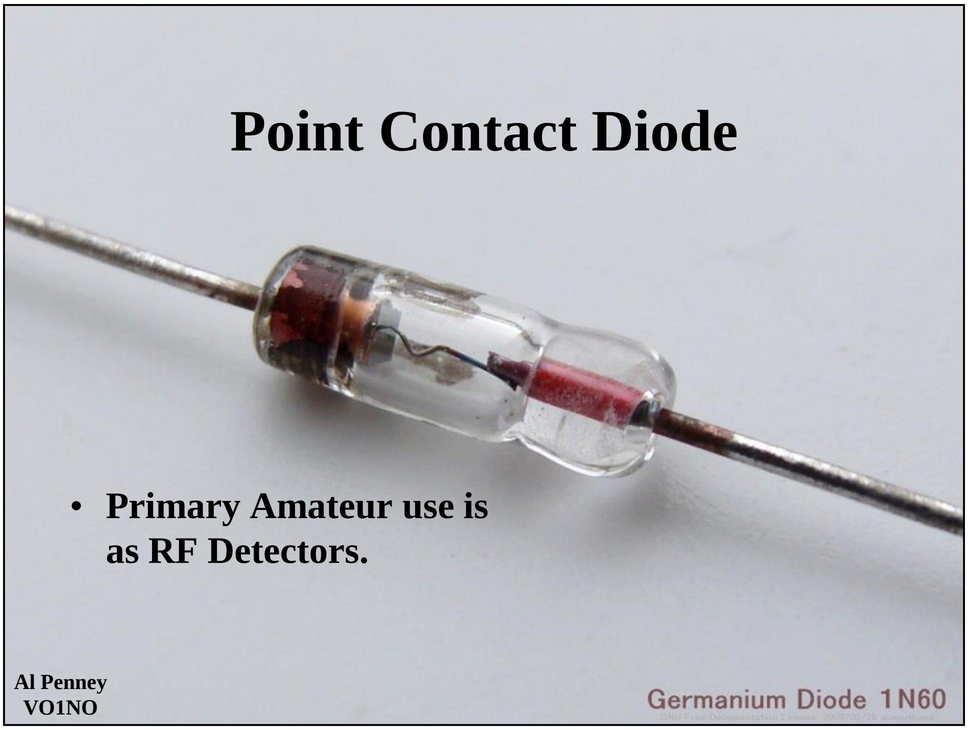
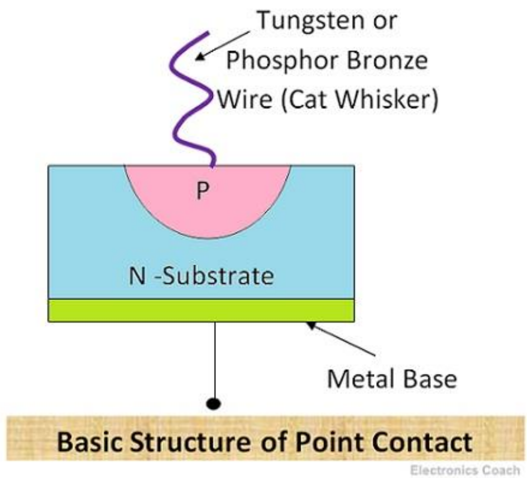
A PN-junction diode is formed when a p-type semiconductor is fused to an n-type semiconductor creating a potential barrier voltage across the diode junction



Point contact diode is formed by touching a metallic wire with an N-type semiconductor to form a small area of contact. This form a **small point junction.** It is widely used because such a small point junction possesses a small value of junction capacitance. Thus, the charge storage at the junction is low. Due to this, the switching ability of diode is much better than a conventional diode.

Point contact diode: This type of diode performs in the same way as a simple PN junction diode, but the construction is much easier. They consist of a piece of n-type semiconductor, onto which a sharp point of a specific type of metal wire (group III metal for chemists) is placed. Some of the metal migrates into the semiconductor and produces a PN junction. These diodes have a very low level of capacitance and are ideal for many radio frequency (RF) applications. They also have the advantage that they are very cheap to manufacture, although their performance is not particularly repeatable.

Point Contact Diode



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Construction of Point Contact Diode

It is formed by a contact of an N-type semiconductor substrate and tungsten or **phosphor bronze wire (Cat whisker)**. The semiconductor used in the construction of point contact diode can be either silicon or germanium but Germanium is used extensively because it possesses higher carrier mobility.

The dimension of the semiconductor substrate is about 1.25 mm square and its thickness is 0.5 mm thick. One phase of the semiconductor substrate is soldered to the metal base by the technique of radio frequency heating.

The cross sectional area of tungsten wire or cat whisker is very small. It is joined to N-type semiconductor but the phase of the substrate joined to cat whisker should be opposite to that of metal contact phase. The anode and cathode terminal are connected through metallic contacts.

Zener Diode

- Special type of rectifying diode that can handle reverse breakdown voltage without failing completely.
- **Maintains a constant voltage under conditions of varying current.**
- Provides a reference voltage for power supply regulator circuits, but can do it by itself if current requirements are low.

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A Zener diode is a special type of rectifying diode that can handle breakdown due to reverse breakdown voltage without failing completely.

The **Zener diode** behaves just like a normal general-purpose diode consisting of a silicon PN junction and when biased in the forward direction, that is Anode positive with respect to its Cathode, it behaves just like a normal signal diode passing the rated current.

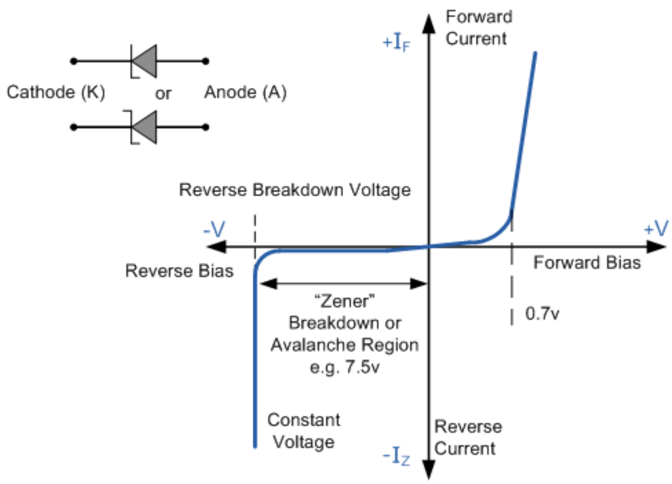
However, unlike a conventional diode that blocks any flow of current through itself when reverse biased, that is the Cathode becomes more positive than the Anode, as soon as the reverse voltage reaches a pre-determined value, the zener diode begins to conduct in the reverse direction.

This is because when the reverse voltage applied across the zener diode exceeds the rated voltage of the device a process called *Avalanche Breakdown* occurs in the semiconductor depletion layer and a current starts to flow through the diode to limit this increase in voltage.

The current now flowing through the zener diode increases dramatically to the maximum circuit value (which is usually limited by a series resistor) and once achieved, this reverse saturation current remains fairly constant over a wide range of reverse voltages. The voltage point at which the voltage across the zener diode becomes stable is called the “zener voltage”, (Vz) and for zener diodes this voltage can range from less than one volt to a few hundred volts.

The point at which the zener voltage triggers the current to flow through the diode can be very accurately controlled (to less than 1% tolerance) in the doping stage of the diodes semiconductor construction giving the diode a specific *zener breakdown voltage*, (Vz) for example, 4.3V or 7.5V. This zener breakdown voltage on the I-V curve is almost a vertical straight line.

Zener Diodes



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The **Zener Diode** or "Breakdown Diode", as they are sometimes referred too, are basically the same as the standard PN junction diode but they are specially designed to have a low and specified **Reverse Breakdown Voltage** which takes advantage of any reverse voltage applied to it.

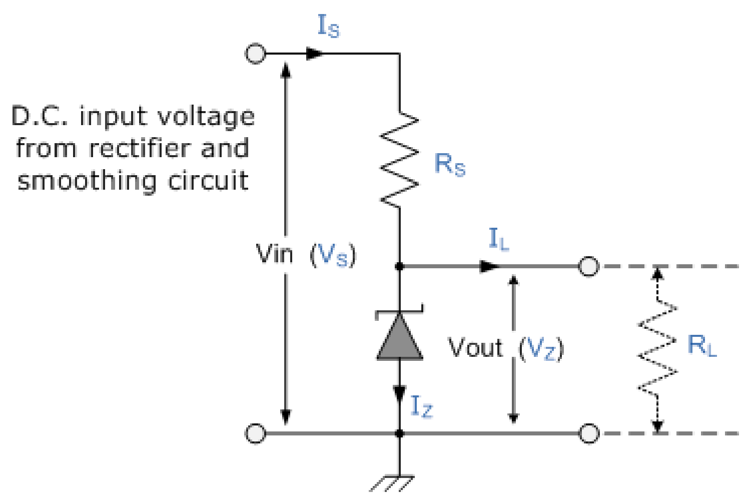
The **Zener Diode** is used in its "reverse bias" or reverse breakdown mode, i.e. the diodes anode connects to the negative supply. From the I-V characteristics curve above, we can see that the zener diode has a region in its reverse bias characteristics of almost a constant negative voltage regardless of the value of the current flowing through the diode.

This voltage remains almost constant even with large changes in current providing the zener diodes current remains between the breakdown current $I_{Z(min)}$ and its maximum current rating $I_{Z(max)}$.

This ability of the zener diode to control itself can be used to great effect to regulate or stabilise a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important characteristic of the zener diode as it can be used in the simplest types of voltage regulator applications.

The function of a voltage regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or variations in the load current. A zener diode will continue to regulate its voltage until the diodes holding current falls below the minimum $I_{Z(min)}$ value in the reverse breakdown region.

Zener Diode Voltage Regulation



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Zener Diodes can be used to produce a stabilised voltage output with low ripple under varying load current conditions. By passing a small current through the diode from a voltage source, via a suitable current limiting resistor (R_S), the zener diode will conduct sufficient current to maintain a voltage drop of Vout.

We remember from the previous tutorials that the DC output voltage from the half or full-wave rectifiers contains ripple superimposed onto the DC voltage and that as the load value changes so to does the average output voltage. By connecting a simple zener stabiliser circuit as shown below across the output of the rectifier, a more stable output voltage can be produced.

Resistor, R_S is connected in series with the zener diode to limit the current flow through the diode with the voltage source, V_S being connected across the combination. The stabilised output voltage V_{out} is taken from across the zener diode.

The zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor R_S is selected so to limit the maximum current flowing in the circuit.

With no load connected to the circuit, the load current will be zero, ($I_L = 0$), and all the circuit current passes through the zener diode which in turn dissipates its maximum power. Also a small value of the series resistor R_S will result in a greater diode current when the load resistance R_L is connected and large as this will increase the power dissipation requirement of the diode so care must be taken when selecting the appropriate value of series resistance so that the zener's maximum power rating is not exceeded under this no-load or high-impedance condition.

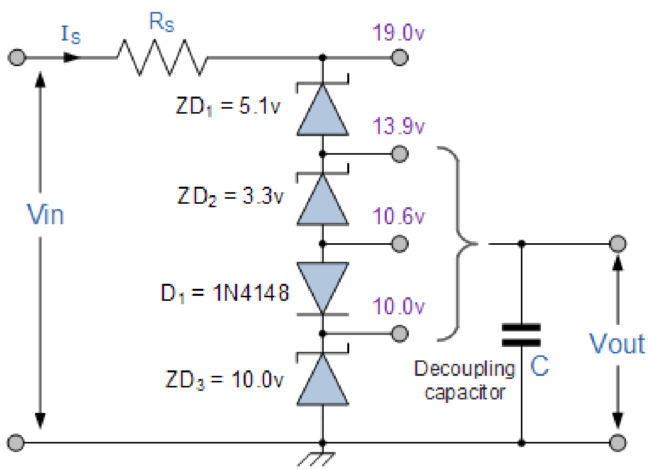
The load is connected in parallel with the zener diode, so the voltage across R_L is always the same as the zener voltage, ($V_R = V_Z$). There is a minimum zener current for which the stabilisation of the voltage is effective and the zener current must stay above this value operating under load within its breakdown region at all times. The upper limit of current is of course dependant upon the power rating of the device. The supply voltage V_S must be greater than V_Z.

One small problem with zener diode stabiliser circuits is that the diode can sometimes generate electrical noise on top of the DC supply as it tries to stabilise the voltage. Normally this is not a problem for most applications but the addition of a large value decoupling capacitor across the zener's output may be required to give additional smoothing.

Then to summarise a little. A zener diode is always operated in its reverse biased condition. As such a simple voltage regulator circuit can be designed using a zener diode to maintain a constant DC output voltage across the load in spite of variations in the input voltage or changes in the load current.

The zener voltage regulator consists of a current limiting resistor R_S connected in series with the input voltage V_S with the zener diode connected in parallel with the load R_L in this reverse biased condition. The stabilised output voltage is always selected to be the same as the breakdown voltage V_Z of the diode.

Zener Diode Voltages



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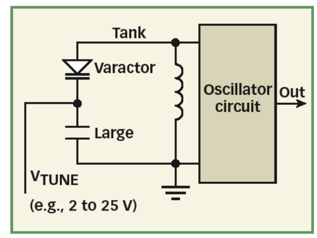
Zener Diode Voltages

As well as producing a single stabilised voltage output, zener diodes can also be connected together in series along with normal silicon signal diodes to produce a variety of different reference voltage output values as shown below.

The values of the individual Zener diodes can be chosen to suit the application while the silicon diode will always drop about 0.6 – 0.7V in the forward bias condition. The supply voltage, Vin must of course be higher than the largest output reference voltage and in our example above this is 19v.

Varactor Diode

- Diode's **capacitance changes** as applied **reverse bias voltage changes**.
- Used as a smaller/cheaper replacement for variable capacitors in radio circuits.
- Also called **varicap** or **tuning diode**.



2. A traditional VCO employs reverse-voltage tuning of a varactor diode to change oscillator frequency.

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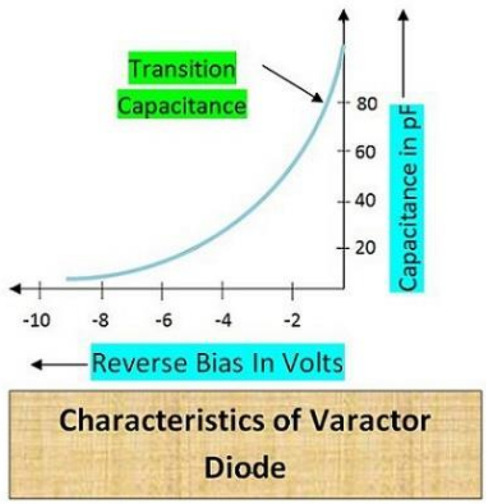
Varicap or varactor diodes

Varactor diode is the one which works on the principle of variation in capacitance by changing the width of the depletion region of P-N junction. The P-N Junction diode creates **capacitor effect**. The capacitance is controlled by applied voltage. It works on **reverse biased** mode.

These are used as voltage-controlled capacitors. These are important in PLL (phase-locked loop) and FLL (frequency-locked loop) circuits, allowing tuning circuits, such as those in television receivers, to lock quickly. They also enabled tunable oscillators in early discrete tuning of radios, where a cheap and stable, but fixed-frequency, crystal oscillator provided the reference frequency for a voltage-controlled oscillator.

Varactor Diode



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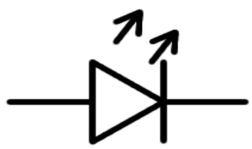
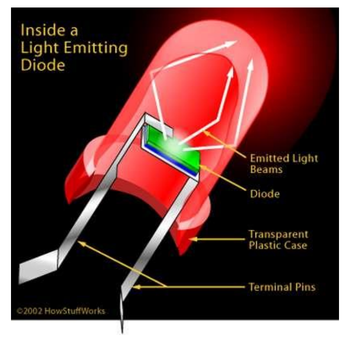
It can be seen in the characteristic curve that as reverse voltage increase from 0 V the transition capacitance is decreasing exponentially.

Light Emitting Diode (LED)

- When forward biased, LEDs emit red, yellow or green light depending on composition of the diode.





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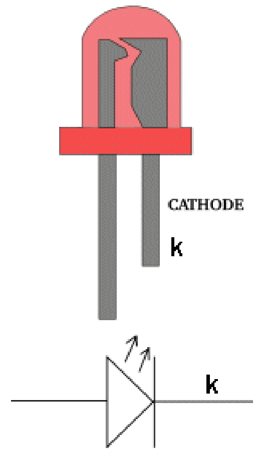
The “**Light Emitting Diode**” or LED as it is more commonly called, is basically just a specialised type of diode as they have very similar electrical characteristics to a PN junction diode. This means that an LED will pass current in its forward direction but block the flow of current in the reverse direction.

Light emitting diodes are made from a very thin layer of fairly heavily doped semiconductor material and depending on the semiconductor material used and the amount of doping, when forward biased an LED will emit a coloured light at a particular spectral wavelength.

When the diode is forward biased, electrons from the semiconductors conduction band recombine with holes from the valence band releasing sufficient energy to produce photons which emit a monochromatic (single colour) of light. Because of this thin layer a reasonable number of these photons can leave the junction and radiate away producing a coloured light output.

Light Emitting Diode (LED)



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The construction of a Light Emitting Diode is very different from that of a normal signal diode. The PN junction of an LED is surrounded by a transparent, hard plastic epoxy resin hemispherical shaped shell or body which protects the LED from both vibration and shock.

Surprisingly, an LED junction does not actually emit that much light so the epoxy resin body is constructed in such a way that the photons of light emitted by the junction are reflected away from the surrounding substrate base to which the diode is attached and are focused upwards through the domed top of the LED, which itself acts like a lens concentrating the amount of light. This is why the emitted light appears to be brightest at the top of the LED.

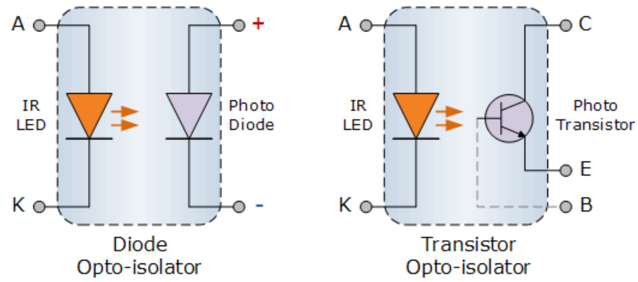
Also, nearly all modern light emitting diodes have their cathode, (–) terminal identified by either a notch or flat spot on the body or by the cathode lead being shorter than the other as the anode (+) lead is longer than the cathode (k).

Unlike normal incandescent lamps and bulbs which generate large amounts of heat when illuminated, the light emitting diode produces a "cold" generation of light which leads to high efficiencies than the normal "light bulb" because most of the generated energy radiates away within the visible spectrum. Because LEDs are solid-state devices, they can be extremely small and durable and provide much longer lamp life than normal light sources.

The actual colour of a light emitting diode is determined by the wavelength of the light emitted, which in turn is determined by the actual semiconductor compound used in forming the PN junction during manufacture.

Therefore the colour of the light emitted by an LED is NOT determined by the colouring of the LED’s plastic body although these are slightly coloured to both enhance the light output and to indicate its colour when its not being illuminated by an electrical supply.

Opto-Coupler



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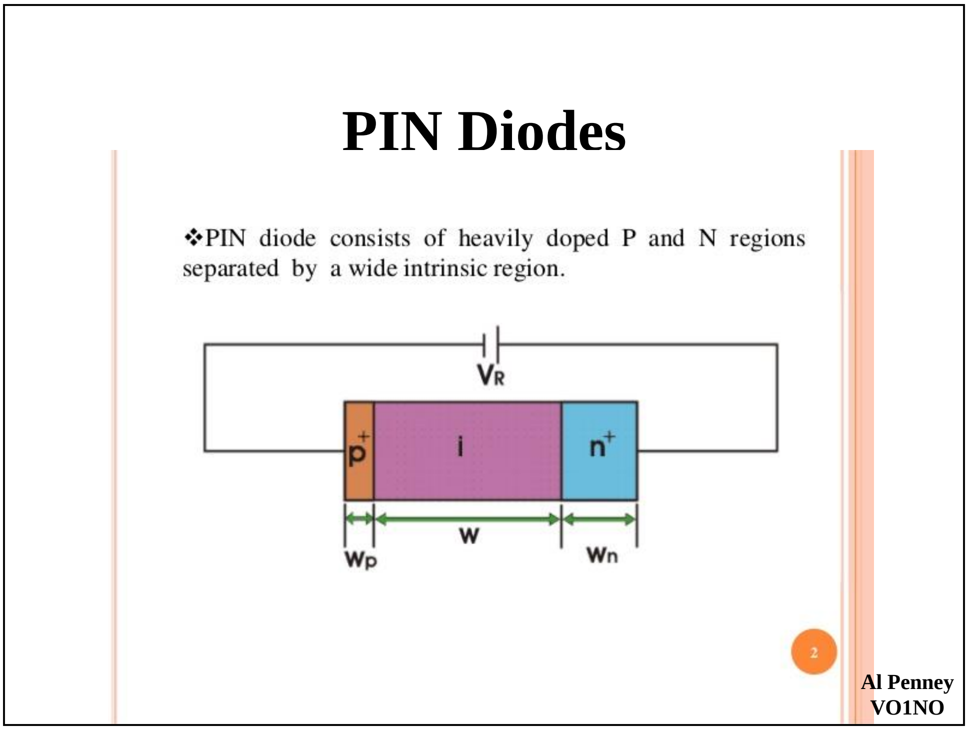
Finally, another useful application of light emitting diodes is in **Opto-coupling**. An opto-coupler or opto-isolator as it is also called, is a single electronic device that consists of a light emitting diode combined with either a photo-diode, photo-transistor or photo-triac to provide an optical signal path between an input connection and an output connection while maintaining electrical isolation between two circuits.

An opto-isolator consists of a light proof plastic body that has a typical breakdown voltages between the input (photo-diode) and the output (photo-transistor) circuit of up to 5000 volts. This electrical isolation is especially useful where the signal from a low voltage circuit such as a battery powered circuit, computer or microcontroller, is required to operate or control another external circuit operating at a potentially dangerous mains voltage.

The two components used in an opto-isolator, an optical transmitter such as an infra-red emitting Gallium Arsenide LED and an optical receiver such as a photo-transistor are closely optically coupled and use light to send signals and/or information between its input and output. This allows information to be transferred between circuits without an electrical connection or common ground potential.

Opto-isolators are digital or switching devices, so they transfer either “ON-OFF” control signals or digital data. Analogue signals can be transferred by means of frequency or pulse-width modulation.



A **PIN diode** is a diode with a wide, undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region. The p-type and n-type regions are typically heavily doped because they are used for ohmic contacts.

The wide intrinsic region is in contrast to an ordinary p–n diode. The wide intrinsic region makes the PIN diode an inferior rectifier (one typical function of a diode), but it makes it suitable for attenuators, fast switches, photodetectors, and high voltage power electronics applications.

A PIN diode operates under what is known as **high-level injection**. In other words, the intrinsic "i" region is flooded with charge carriers from the "p" and "n" regions. Its function can be likened to filling up a water bucket with a hole on the side. Once the water reaches the hole's level it will begin to pour out. Similarly, the diode will conduct current once the flooded electrons and holes reach an equilibrium point, where the number of electrons is equal to the number of holes in the intrinsic region. When the diode is forward biased, the injected carrier concentration is typically several orders of magnitude higher than the intrinsic carrier concentration. Due to this high level injection, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from the P to the N region, which results in faster operation of the diode, making it a suitable device for high frequency operations.

The term PIN diode gets its name from the fact that includes three main layers. Rather than just having a P-type and an N-type layer, it has three layers:

- P-type layer
- Intrinsic layer
- N-type layer

The working principle of the PIN diode exactly same as a normal diode. The main difference is that the depletion region, because that normally exists between both the P & N regions in a reverse biased or unbiased diode is larger. In any PN junction diode, the P region contains holes as it has been doped to make sure that it has a majority of holes. Likewise the N-region has been doped to hold excess electrons.

The layer between the P & N regions includes no charge carriers as any electrons or holes merge As the depletion region of the diode has no charge carriers it works as an insulator. The depletion region exists within a PIN diode, but if the PIN diode is forward biased, then the carriers come into the depletion region and as the two carrier types get together, the flow of current will starts.

When the PIN diode is connected in forward biased, the charge carriers are very much higher than the level of intrinsic carrier’s attention. Due to this reason the electric field and the high level injection level extends deeply into the region. This electric field assists in speeding up of the moving of charge carriers from P to N region, which consequences in quicker operation of the PIN diode, making it an appropriate device for high frequency operations.

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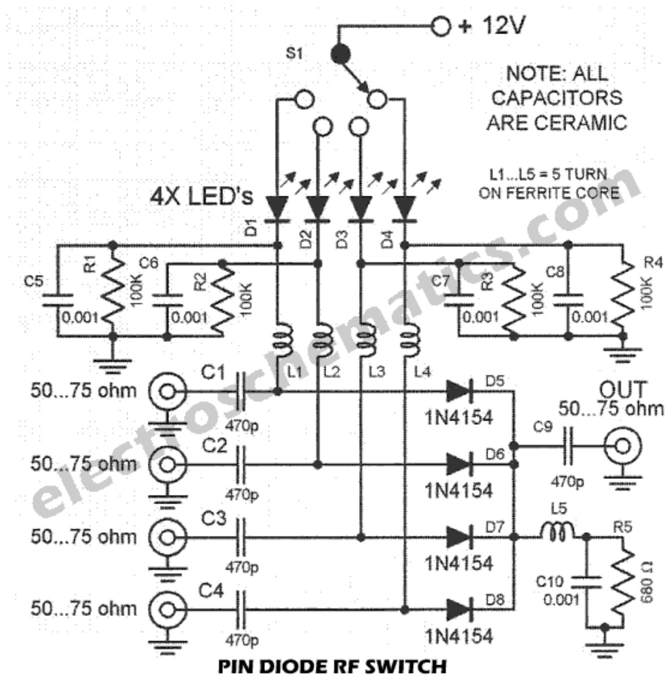
A wide frequency, microwave (0.1 to 20 GHz), high-performance, reflective, SPDT switch, using PIN diodes

At high frequencies, the PIN diode appears as a resistor whose resistance is an inverse function of its forward current. Consequently, PIN diode can be used in some variable attenuator designs as amplitude modulators or output leveling circuits.

Conventional diodes are unsuitable for RF switching because the junction capacitance allows AC to pass even when reverse biased.



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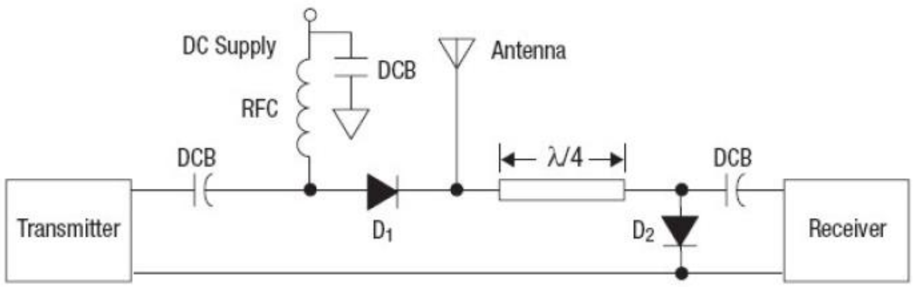
PIN Diode TR Switch



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In this design, both PIN diodes are forward biased in the transmit state with the series connected diode, D1, allowing a low insertion loss path between transmitter and antenna and the receiver protected by the low impedance of the shunt diode, D2. This low impedance is transformed by a quarter wave transformer which projects high impedance to the antenna terminal. In the receive state both PIN diodes may be at zero bias; thus in this configuration the switch requires no energy. This design is also limited in its power handling by utilizing a series connected diode in the transmit arm. It should also be noted

that, during transmit, the shunt diode in the receiver arm is carrying the same RF

current as the antenna and must have adequate power dissipation capability.

Gunn Diode

- Used to **generate microwave** signals from 1 to 150 GHz.
- Consists of N type material doped to different concentrations in 3 regions.

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Gunn diodes have been available for many years and they form a very effective method of generating microwave signals anywhere from around 1 GHz up to frequencies of possibly 100 GHz.

Gunn diodes are also known as transferred electron devices, TED. Although is referred to as a diode, the devices does not possess a PN junction. Instead the device uses an effect known as the Gunn effect (named after the discoverer, J B Gunn).

Although the Gunn diode is normally used for generating microwave RF signals, the Gunn diode may also be used for an amplifier in what may be known as a transferred electron amplifier or TEA.

As Gunn diodes are easy to use, they form a relatively low cost method for generating microwave RF signals, often being mounted within a waveguide to form a simple resonant cavity.

Gunn Diode

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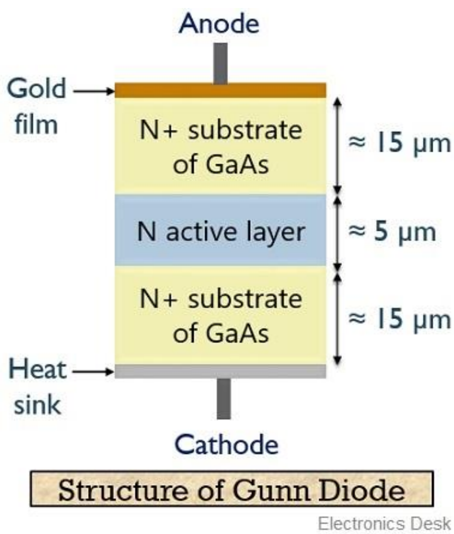
A **Gunn diode**, also known as a **transferred electron device** (**TED**), is a form of diode, a two-terminal passive semiconductor electronic component, with negative resistance, used in high-frequency electronics. It is based on the "Gunn effect" discovered in 1962 by physicist J. B. Gunn. Its largest use is in electronic oscillators to generate microwaves, in applications such as radar speed guns, microwave relay data link transmitters, and automatic door openers.

Its internal construction is unlike other diodes in that it consists only of N-doped semiconductor material, whereas most diodes consist of both P and N-doped regions. It therefore does not conduct in only one direction and cannot rectify alternating current like other diodes, which is why some sources do not use the term *diode* but prefer TED. In the Gunn diode, three regions exist: two of those are heavily N-doped on each terminal, with a thin layer of lightly n-doped material between. When a voltage is applied to the device, the electrical gradient will be largest across the thin middle layer. If the voltage is increased, the current through the layer will first increase, but eventually, at higher field values, the conductive properties of the middle layer are altered, increasing its resistivity, and causing the current to fall. This means a Gunn diode has a region of negative differential resistance in its current-voltage characteristic curve, in which an increase of applied voltage, causes a decrease in current. This property allows it to amplify, functioning as a radio frequency amplifier, or to become unstable and oscillate when it is biased with a DC voltage.

Gunn Diode



Symbol of Gunn Diode

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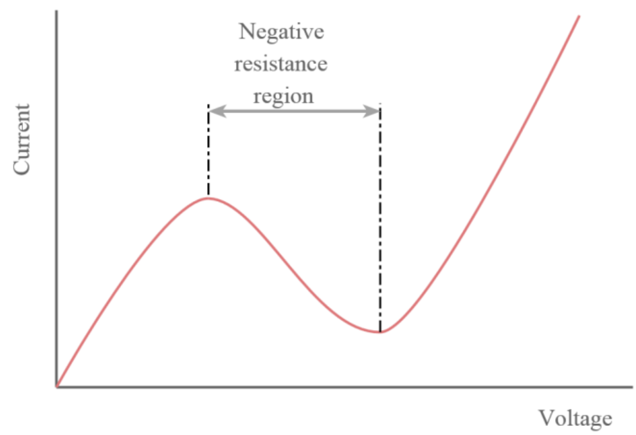
In 1963 **John Battiscombe Gunn (J.B. Gunn)** as a first person has observed that in the wafers of gallium arsenide with a very small thickness, after supplying them with a sufficiently large voltage, **very high oscillation frequencies were generated**. They are usually made of **gallium arsenide (GaAs)** and their maximum operating frequency is about 200 GHz. However, Gunn diodes made from Gallium Nitride (GaN) elements can reach up to 3 THz. On a daily basis, Gunn diodes are used in high-frequency electronics as a **source of great output power and high frequency.** After joining resonator to a diode, we can obtain sinusoidal voltage. Just to let you know, in case of this article the author will use "Gunn diode" name most of the time. Microwave diodes are usually used as a substitute for germanium diodes when **low threshold voltage VT is required** (approx. 0.3-0.4 V). Gunn diodes have **very fast** switching times due to their construction and operating principles. They are used in detecting technologies, radar speed guns, relays or microwave trackers.

Gunn Diode



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The Gunn diode is a unique component - even though it is called a diode, it does not contain a PN diode junction. The Gunn diode or transferred electron device can be termed a diode because it has two electrodes.

The Gunn diode operation depends on the fact that it has a voltage controlled negative resistance – this being dependent upon the fact that when a voltage is placed across the device, most of the voltage appears across the inner active region. This inner region is particularly thin and this means that the voltage gradient that exists in this region is exceedingly high.

The device exhibits a negative resistance region on its V/I curve as seen below. This negative resistance area enables the Gunn diode to amplify signals, enabling it to be used in amplifiers and oscillators. However it is the Gunn diode oscillators are the most commonly used.

This negative resistance region means that the current flow in diode increases in the negative resistance region when the voltage falls - the inverse of the normal effect in any other positive resistance element. This phase reversal enables the Gunn diode to act as an amplifier and as an oscillator.

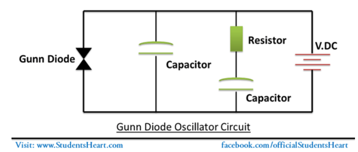
Whilst the Gunn diode has a negative resistance region, it is interesting to see a little more about how this happens and how it acts as an oscillator.

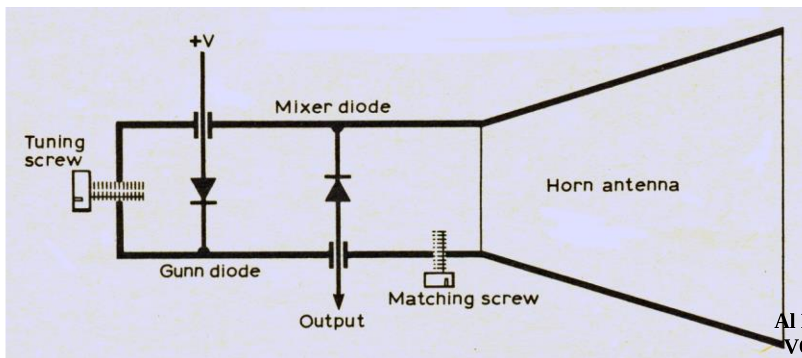
At microwave frequencies, it is found that the dynamic action of the diode incorporates elements resulting from the thickness of the active region.

When the voltage across the active region reaches a certain point a current is initiated that travels across the active region. During the time when the current pulse is moving across the active region the potential gradient falls preventing any further pulses from forming. Only when the pulse has reached the far side of the active region will the potential gradient rise, allowing the next pulse to be created.

It can be seen that the time taken for the current pulse to traverse the active region largely determines the rate at which current pulses are generated. It is this that determines the frequency of operation.

Gunn Diode Oscillator Circuit





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It can be seen that the time taken for the current pulse to traverse the active region largely determines the rate at which current pulses are generated. It is this, plus the dimensions of the cavity resonator, that determines the frequency of operation.

Schottky / Hot Carrier Diode

- Forward voltage drop is significantly less than other silicon junction diodes.
- Constructed using a metal electrode bonded to an N-type semiconductor.
- Low power and fast switching speed.
- Used for rectification, signal conditioning and switching.
- **Primary Amateur application is VHF/UHF mixers and detectors.**

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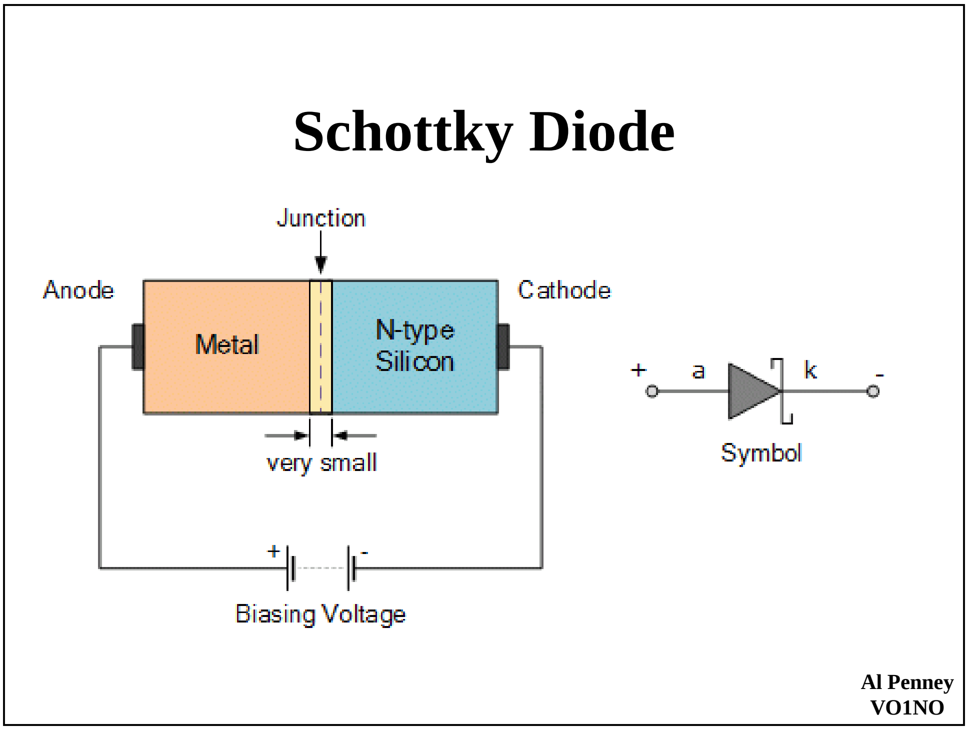
The **Schottky Diode** is another type of semiconductor diode but have the advantage that their forward voltage drop is substantially less than that of the conventional silicon pn-junction diode.



When sufficient forward voltage is applied, a current flows in the forward direction. A silicon diode has a typical forward voltage of 600–700 mV, while the Schottky's forward voltage is 150–450 mV. This lower forward voltage requirement allows higher switching speeds and better system efficiency.

The **Schottky Diode** is another type of semiconductor diode but have the advantage that their forward voltage drop is substantially less than that of the conventional silicon pn-junction diode.

Schottky diodes have many useful applications from rectification, signal conditioning and switching, through to TTL and CMOS logic gates due mainly to their low power and fast switching speeds. TTL Schottky logic gates are identified by the letters LS appearing somewhere in their logic gate circuit code, e.g. 74LS00.

Unlike a conventional pn-junction diode which is formed from a piece of P-type material and a piece of N-type material, Schottky Diodes are constructed using a metal electrode bonded to an N-type semiconductor. Since they are constructed using a metal compound on one side of their junction and doped silicon on the other side, the

Schottky diode therefore has no depletion layer and are classed as unipolar devices unlike typical pn-junction diodes which are bipolar devices.

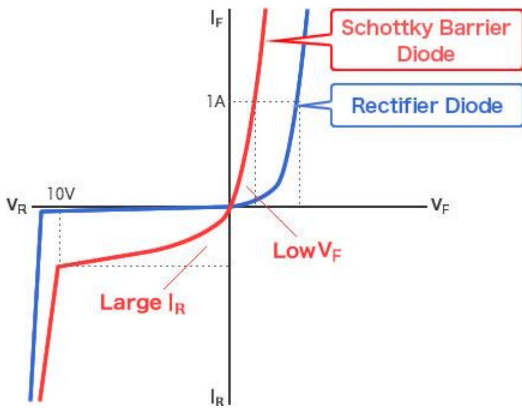
The most common contact metal used for Schottky diode construction is "Silicide" which is a highly conductive silicon and metal compound. This silicide metal-silicon contact has a reasonably low ohmic resistance value allowing more current to flow producing a smaller forward voltage drop of around $Vf < 0.4V$ when conducting. Different metal compounds will produce different forward voltage drops, typically between 0.3 to 0.5 volts.

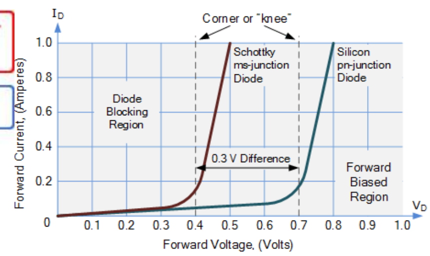
Above shows the simplified construction and symbol of a Schottky diode in which a lightly doped n-type silicon semiconductor is joined with a metal electrode to produce what is called a "metal-semiconductor junction". The width of the ms-junction will depend on the type of metal and semiconductor material used, but when forward-biased, electrons move from the n-type material to the metal electrode allowing current to flow. Thus current through the Schottky diode is the result of the drift of majority carriers.

Since there is no p-type semiconductor material and therefore no minority carriers (holes), when reverse biased, the diodes conduction stops very quickly and changes to blocking current flow, as for a conventional pn-junction diode. Thus for a Schottky diode there is a very rapid response to changes in bias and demonstrating the characteristics of a rectifying diode.

As discussed previously, the knee voltage at which a Schottky diode turns "ON" and starts conducting is at a much lower voltage level than its pn-junction equivalent as shown in the following I-V characteristics.

Schottky Diode Voltage





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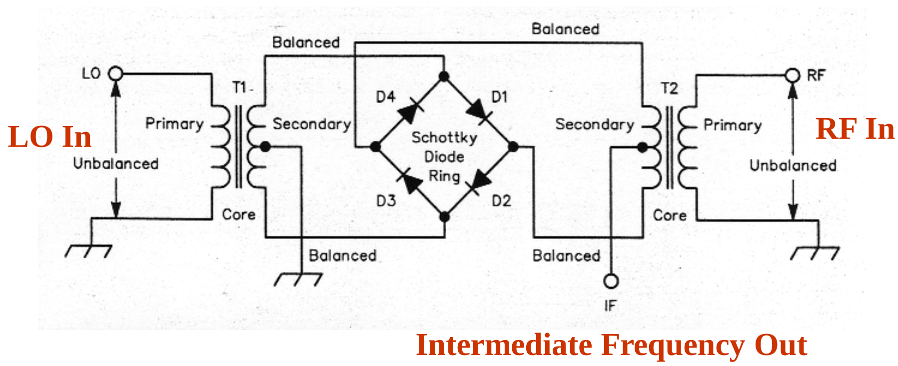
As we can see, the general shape of the metal-semiconductor Schottky diode I-V characteristics is very similar to that of a standard pn-junction diode, except the corner or knee voltage at which the ms-junction diode starts to conduct is much lower at around 0.4 volts.

Due to this lower value, the forward current of a silicon Schottky diode can be many times larger than that of a typical pn-junction diode, depending on the metal electrode used. Remember that Ohms law tells us that power equals volts times amps, (P = V*I) so a smaller forward voltage drop for a given diode current, I_D will produce lower forward power dissipation in the form of heat across the junction.

This lower power loss makes the Schottky diode a good choice in low-voltage and high-current applications such as solar photovoltaic panels where the forward-voltage, (V_F) drop across a standard pn-junction diode would produce an excessive heating effect. However, it must be noted that the reverse leakage current, (I_R) for a Schottky diode is generally much larger than for a pn-junction diode.

Schottky Diode Mixer



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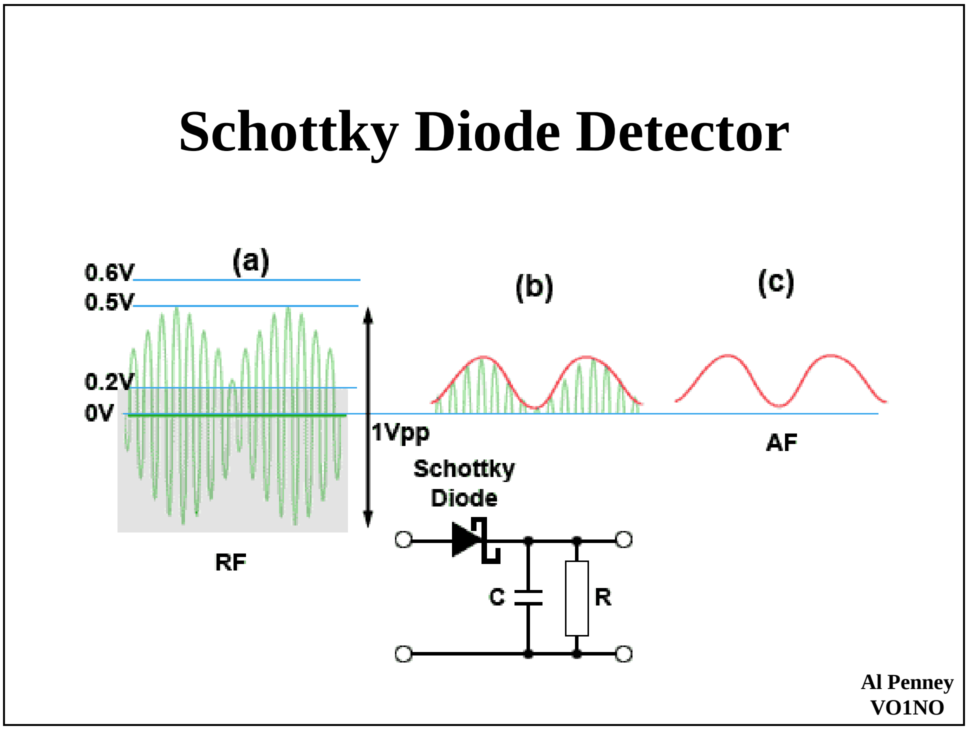
Basic Double Balanced Mixer Function

Applied to the diode ring's D4-D1 and D2-D3 terminals via T1, a 1:4transformer, LO energy forces D1 and D2 into full conduction on each positive half cycle of the LO waveform. D3 and D4 conduct on each negative half cycle. T2, also a 1:4 transformer, applies the RF-port signal to the ring's D1-D2 and D3-D4 terminals. The LO (fLO) switches the RF signal (fRF) to the IF port at the LO frequency, resulting in RF/LO frequency multiplication. The resultant IF-port signal includes two dominant components, fLO+fRF and fLO-fRF, in addition to harmonic products offLO and fRF.

The degree to which a mixer is balanced depends on whether either, neither or both of its input signals (RF and LO) emerge from the IF port along with mixing products. An unbalanced mixer suppresses neither its RF nor its LO; both are present at its IF port. A single-balanced mixer suppresses its RF or LO, but not both. A double-balanced mixer suppresses its RF and LO inputs. Diode and transformer uniformity in the Fig 1 circuit results in equal LO potentials at the center taps of T1 and T2. The LO potential at TI's secondary is zero (ground); therefore, the LO potential at the IF port is zero.

Balance in T2's secondary likewise results in an RF null at the IF port. The RF potential between the IF port and ground is therefore zero.

The Fig 1 circuit normally also affords high RF-LO isolation because its diode switching precludes direct connections between TI and T2. A diode DBM can be used as a current-controlled switch or attenuator by applying dc to its IF port. This causes opposing diodes (D2 and D4, for instance) to conduct to a degree that depends on the current magnitude, connecting T1 to T2.

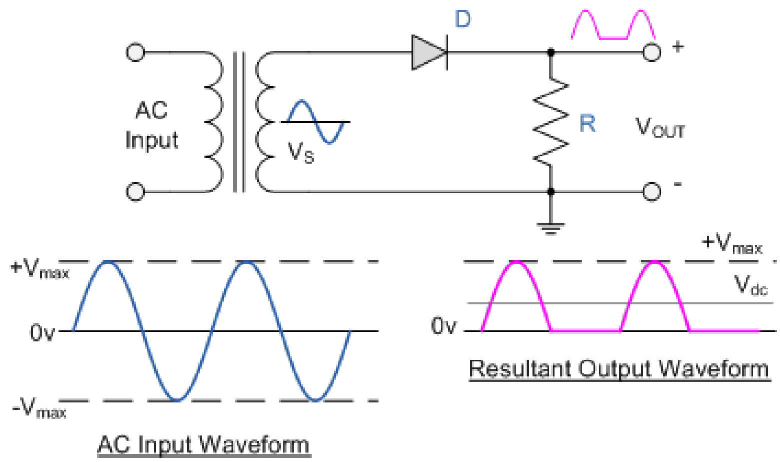


Basic AM Demodulation

Fig. 2.2.4 illustrates the advantage of using Schottky diodes for demodulating small amplitude AM waves. Amplitude Modulated signals are used in both broadcasts and communictaions as they can be transmitted over much longer distances using relatively low power transmitters than would be possible using VHF or UHF signals. When an AM signal is recieved its amplitude at the receiver may only be a few millivolts or even microvolts. This signal is greatly amplified by the receiver but may still be quite small (e.g. 1Vpp as shown in Fig. 2.2.4) when it is applied to the demodulator to recover the modulating signal. It would not therefore have sufficient amplitude (0.5V) to overcome the junction voltage of a silicon PN diode (0.6V), so no signal would be demodulated. Using a Schottky diode with a junction potential of only 0.2V however allows the demodulator to produce usable information from weaker signals than would be possible using a silicon PN diode.

The demodulation process involves applying the amplitude modulated signal to the Schottky diode, which only conducts when the positive half cycles of the RF are greater than 0.2V. (Fig. 2.2.4a) This produces an assymetrical RF signal that is applied to the capacitor C, which charges to nearly the peak value of each half cycle of the RF to produce a signal, (Fig. 2.2.4b) following the envelope shape of the RF signal, this is now an audio frequency waveform (shown in red)(Fig. 2.2.4c) that varies with the same shape as the audio signal originally used to modulate the RF. This demodulated audio signal is now amplified and used to drive the radio loudspeaker

Diodes in Half Wave Rectifiers



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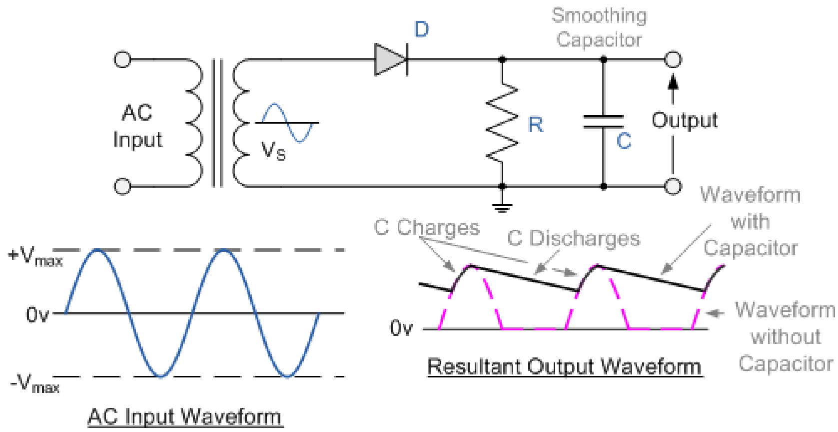
Half Wave Rectifier with a Capacitor



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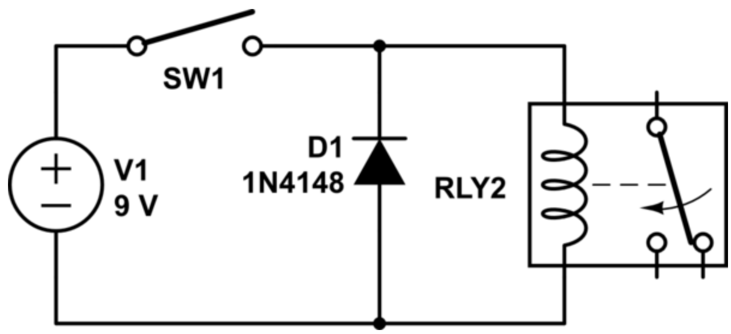
Flyback Diode



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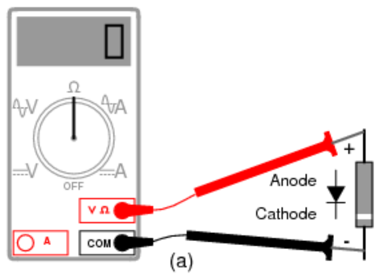
A flyback diode, is a diode that is placed with reverse polarity from the power supply and in parallel to the relay's inductance coil. It is used to prevent the huge voltage spikes that happen when the power supply is disconnected. They are sometimes called "snubber diodes" and are a type of snubber circuit.

When the power supply is connected to the relay, the inductance coil's voltage builds up to match that of the power source. The speed at which current can change in an inductor is limited by its time constant. In this case, the time it takes to minimize current flow through the coil is longer than the time it takes for the power supply to be removed. Upon disconnection, the inductance coil reverses its polarity in an attempt to keep current flowing according to its dissipation curve (i.e., % of maximum current flow with respect to time). This causes a huge voltage potential to build up on the open junctions of the component that controls the relay.

This voltage built up is called flyback voltage. It can result in an electrical arc and damage the components controlling the relay. It can also introduce electrical noise that can couple into adjacent signals or power connections and cause microcontrollers to crash or reset. If you have an electronics control panel that resets each time a relay is de-energized, it's highly possible you have an issue with flyback voltage.

To mitigate this issue, a diode is connected with reverse polarity to the power supply. No current passes through the diode when the relay is energized. When the power supply is removed, the voltage polarity on the coil is inverted, and the diode becomes forward biased. The diode allows current to pass with minimal resistance and prevents flyback voltage from building up. Hence why it is called a flyback diode.

Checking Diodes



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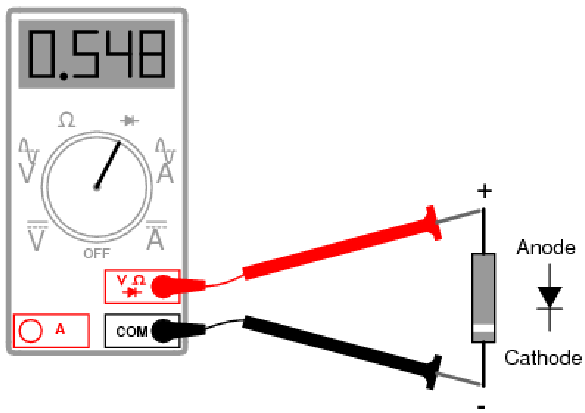
Being able to determine the polarity (cathode versus anode) and basic functionality of a diode is a very important skill for the electronics hobbyist or technician to have. Since we know that a diode is essentially nothing more than a one-way valve for electricity, it makes sense we should be able to verify its one-way nature using a DC (battery-powered) ohmmeter as in Figure below. Connected one way across the diode, the meter should show a very low resistance at (a). Connected the other way across the diode, it should show a very high resistance at (b) ("OL" on some digital meter models).

Of course, to determine which end of the diode is the cathode and which is the anode, you must know with certainty which test lead of the meter is positive (+) and which is negative (-) when set to the "resistance" or "Ω" function. With most digital multimeters I've seen, the red lead becomes positive and the black lead negative when set to measure resistance, in accordance with standard electronics color-code convention. However, this is not guaranteed for all meters. Many analog multimeters, for example, actually make their black leads positive (+) and their red leads negative (-) when switched to the "resistance" function, because it is easier to manufacture it that way!

One problem with using an ohmmeter to check a diode is that the readings obtained only have qualitative value, not quantitative. In other words, an ohmmeter only tells you which way the diode conducts; the low-value resistance indication obtained while conducting is useless. If an ohmmeter shows a value of “1.73 ohms” while forward-biasing a diode, that figure of 1.73 Ω doesn't represent any real-world quantity useful to us as technicians or circuit designers. It neither represents the forward voltage drop nor any “bulk” resistance in the semiconductor material of the diode itself, but rather is a figure dependent upon both quantities and will vary substantially with the particular ohmmeter used to take the reading.

Diode Check Function



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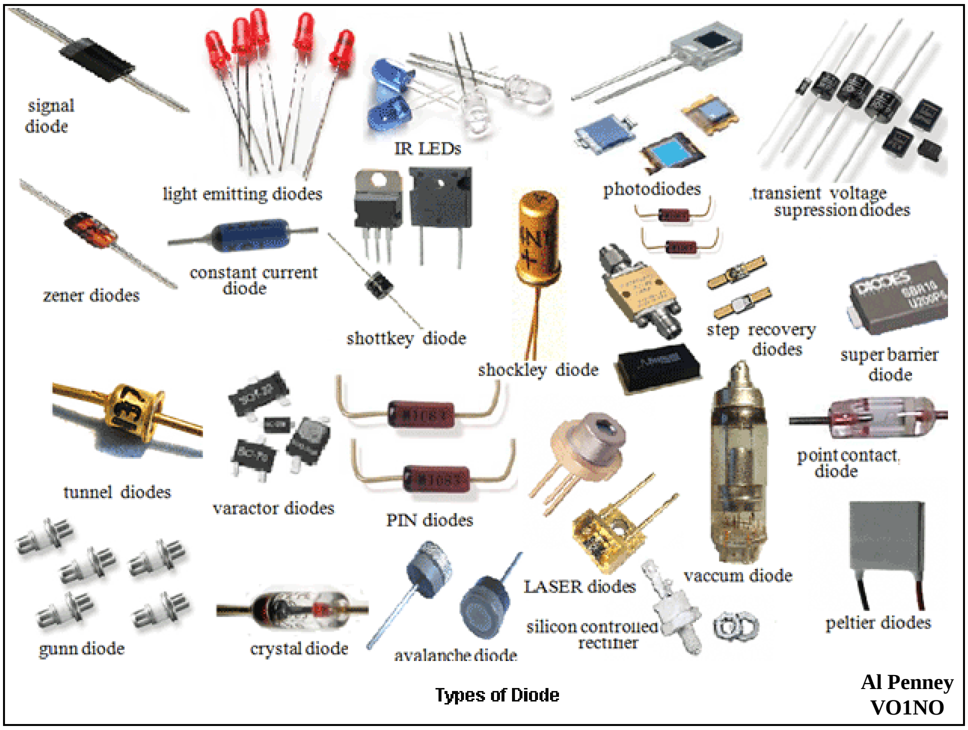
For this reason, some digital multimeter manufacturers equip their meters with a special "diode check" function which displays the actual forward voltage drop of the diode in volts, rather than a "resistance" figure in ohms. These meters work by forcing a small current through the diode and measuring the voltage dropped between the two test leads.



signal diode
light emitting diodes
IR LEDs
photodiodes
transient voltage supression diodes
zener diodes
constant current diode
shottkey diode
shockley diode
step recovery diodes
super barrier diode
tunnel diodes
varactor diodes
PIN diodes
point contact diode
LASER diodes
vaccum diode
gunn diode
crystal diode
avalanche diode
silicon controlled rectifier
peltier diodes
Types of Diode
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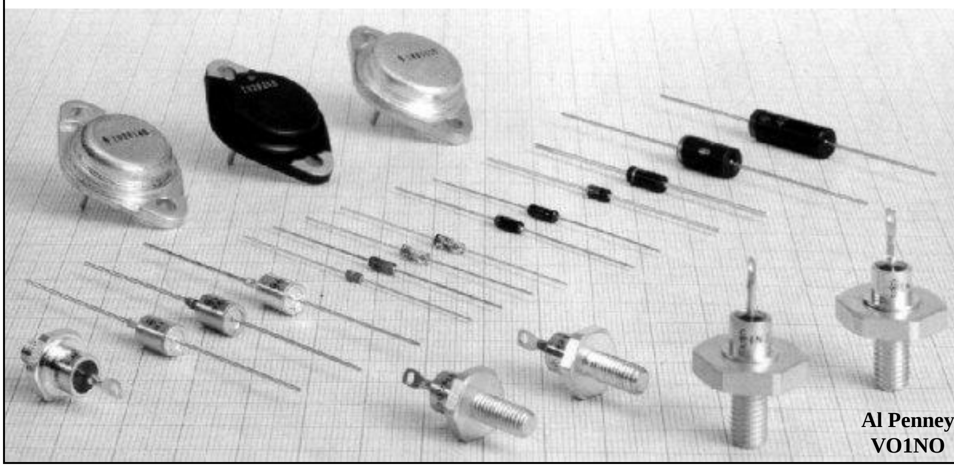
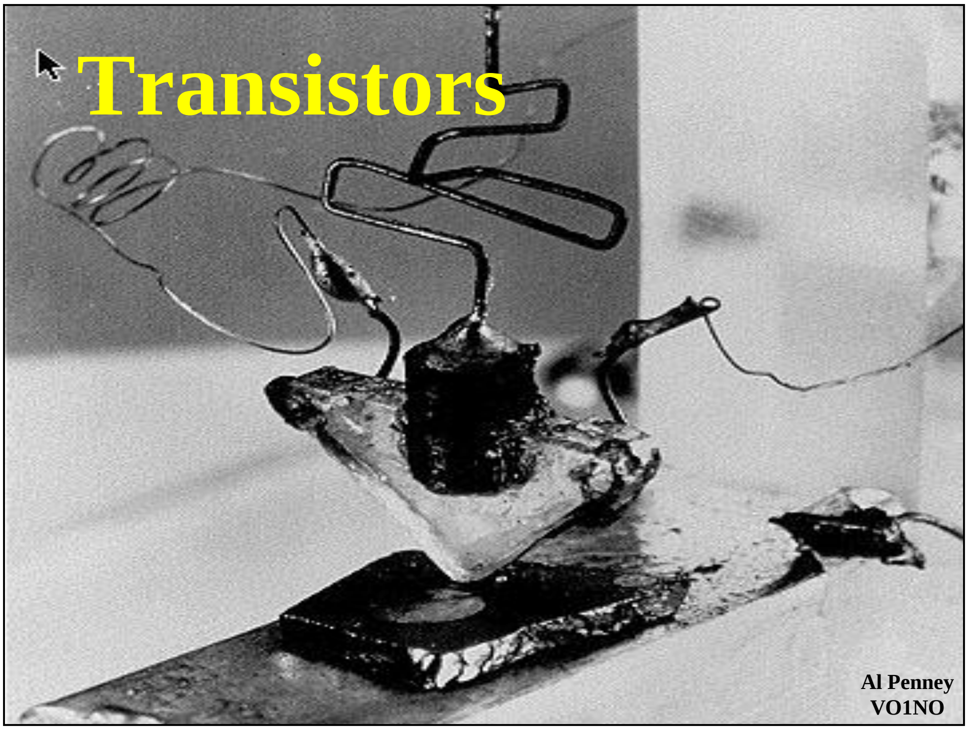
Questions?



Transistors



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What do Transistors do?

- **Switch current** on and off
  - Computer and digital circuits
- **Control current** in a continuous manner
  - Amplifiers
  - Control circuits

Typical transistor packages

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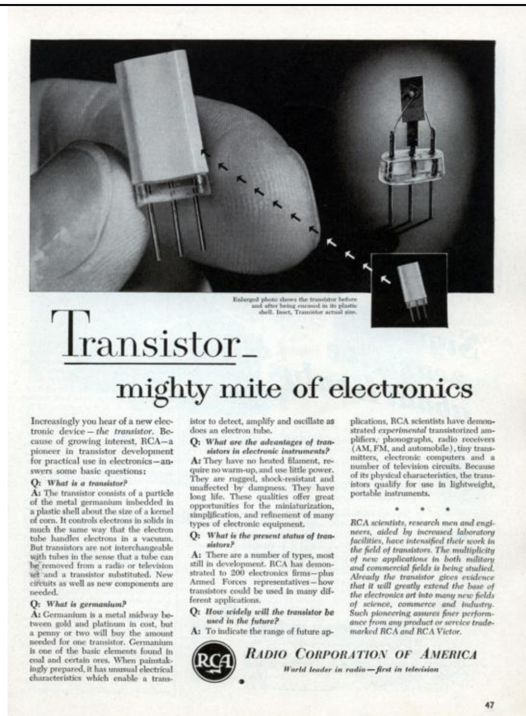

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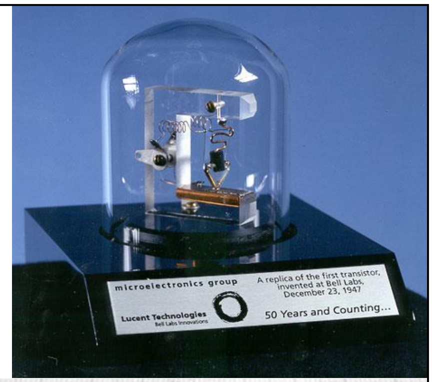
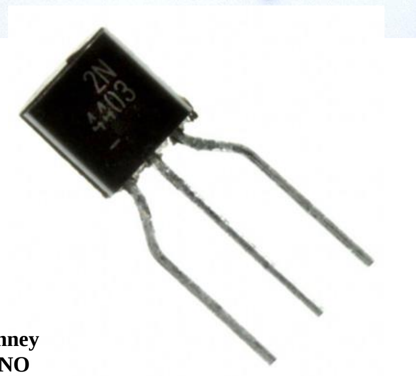
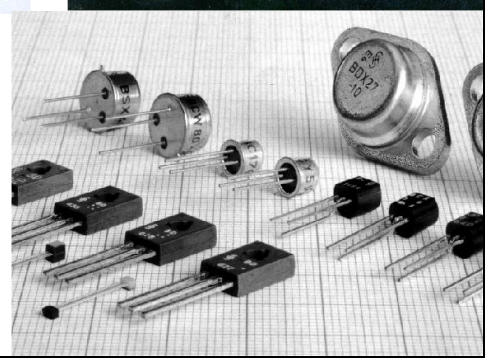
From November 17, 1947, to December 23, 1947, John Bardeen and Walter Brattain at AT&T's Bell Labs in Murray Hill, New Jersey of the United States performed experiments and observed that when two gold point contacts were applied to a crystal of germanium, a signal was produced with the output power greater than the input.[12] Solid State Physics Group leader William Shockley saw the potential in this, and over the next few months worked to greatly expand the knowledge of semiconductors. The term *transistor* was coined by John R. Pierce as a contraction of the term *transresistance*.[13][14][15] According to Lillian Hoddeson and Vicki Daitch, authors of a biography of John Bardeen, Shockley had proposed that Bell Labs' first patent for a transistor should be based on the field-effect and that he be named as the inventor. Having unearthed Lilienfeld's patents that went into obscurity years earlier, lawyers at Bell Labs advised against Shockley's proposal because the idea of a field-effect transistor that used an electric field as a "grid" was not new. Instead, what Bardeen, Brattain, and Shockley invented in 1947 was the first point-contact transistor.[10] In acknowledgement of this accomplishment, Shockley, Bardeen, and Brattain were jointly awarded the 1956 Nobel Prize in Physics "for their researches on semiconductors and their discovery of the transistor effect".[16]







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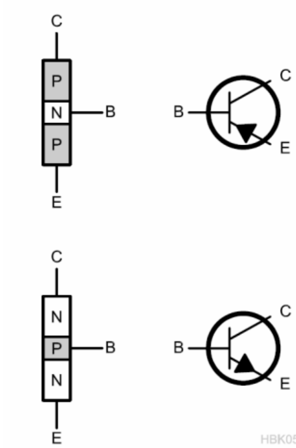
Bipolar Junction Transistor (BJT) Construction

- Stack 3 slices of doped material together.
- **PNP** Transistor
  - “P in P” for arrow
- **NPN** Transistor
  - Arrow points out



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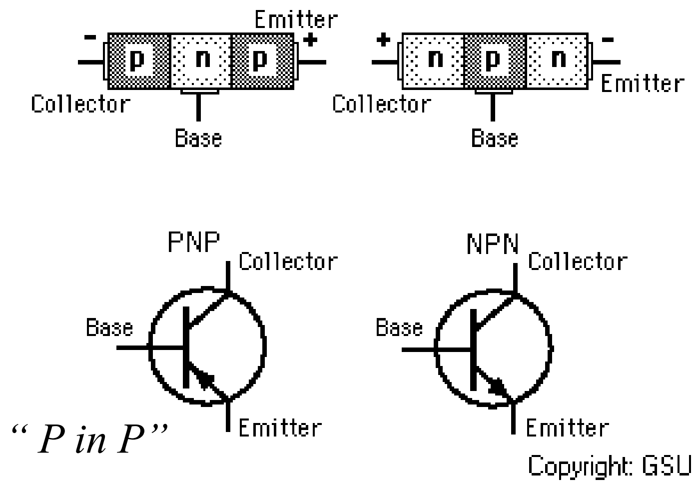
The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.

Bipolar Transistors are current regulating devices that control the amount of current flowing through them from the Emitter to the Collector terminals in proportion to the amount of biasing voltage applied to their base terminal, thus acting like a current-controlled switch. As a small current flowing into the base terminal controls a much larger collector current forming the basis of transistor action.

The principle of operation of the two transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Junction Transistors



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Bipolar Junction Transistors

- Three terminal active devices that can act as either an insulator or a conductor by the application of a small signal voltage.
- Two basic functions:
  - "switching" (digital electronics); or
  - "amplification" (analogue electronics).

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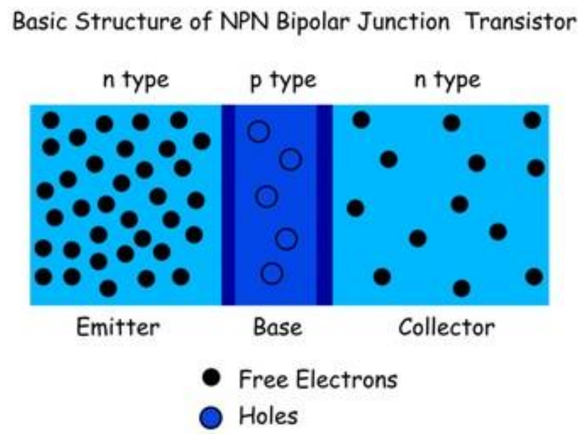
NPN BJT



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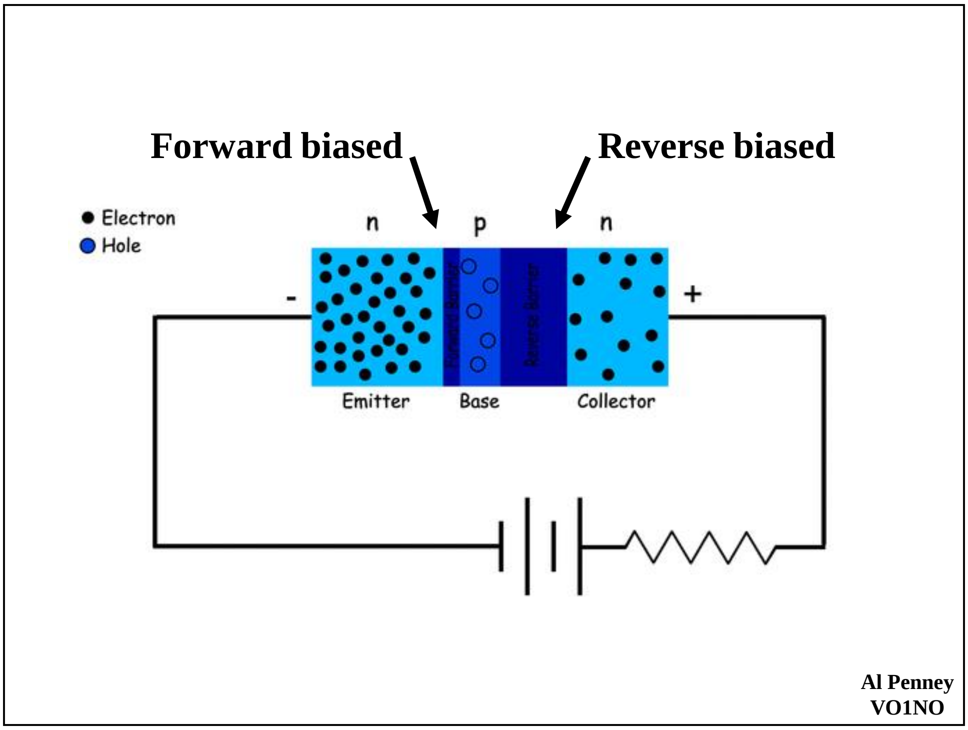
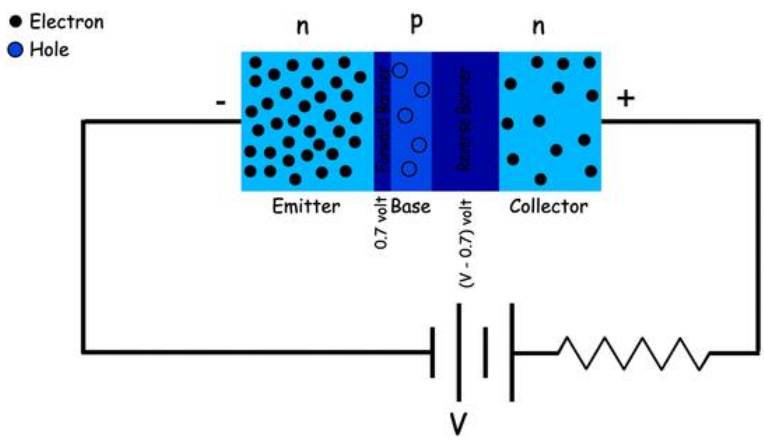
There are different types of transistor available in the market, but for sake of understanding, we will consider a common emitter mode of NPN transistor. For this let us recall the basic structural features of npn bipolar junction transistor. Its emitter region is heavily doped and wider hence the number of free electrons (majority carriers) is large here. The collector region is also wider but it is moderately doped hence the number of free electrons is not as much as the emitter region. The base region is diffused in between the wider emitter and collector region but the base region is quite thin compared to the outer emitter and collector region and also it is very lightly doped so the number of holes (majority carriers) is quite small here.



Now, we connect one battery in between emitter and collector. The emitter terminal of the transistor is connected to the negative terminal of the battery. Hence the emitter-base junction becomes forward biased, and base-collector junction becomes reverse biased.

In this condition, no current will flow through the device. Before going to the actual operation of the device let us recall the constructional and doping details of an NPN transistor. Here the emitter region is wider and very heavily doped. Hence the concentration of majority carriers (free electrons) in this region of the transistor is very high. The base region, on the other hand, is very thin it is in the range of few micrometers whereas emitter and collector region are in the range of millimeter. The doping of the middle p-type layer is very low, and as a result, there is a very tiny number of holes present in this region. The collector region is wider as we already told and doping here is a moderate and hence moderate number of free electrons present in this region.



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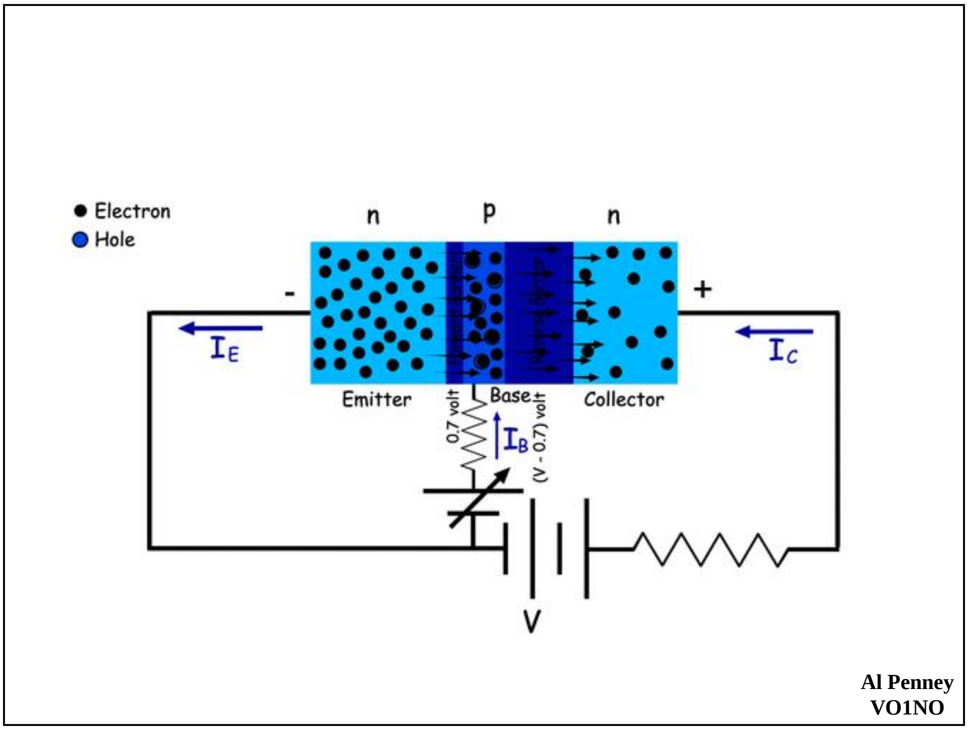
The entire voltage applied between emitter and collector is dropped at two places. One is at the forward barrier potential across the emitter-base junction and this is about 0.7 volt in case of silicon made transistors. The rest portion of the applied voltage is dropped as a reverse barrier across the base-collector junction. Whatever may be the voltage across the device the forward barrier potential across emitter-base junction always remains 0.7 volts and the rest of the source voltage is dropped across the base-collector junction as reverse barrier potential. That means none of the collector voltage can overcome the forward barrier potential. Hence ideally none of the free electrons in the emitter region can cross the forward barrier potential and can come to the base region. As a result of the transistor will behave as an off switch.

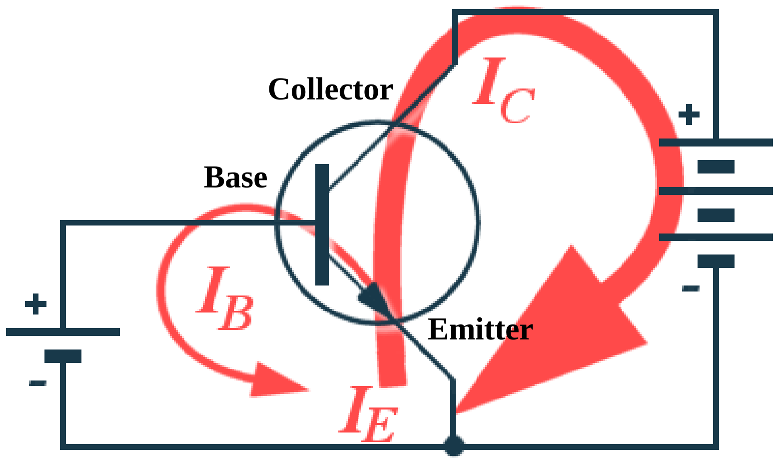
NB: – As at this condition the transistor does not conduct any current ideally, there will be no voltage drop at the external resistance hence entire source voltage (V) will drop across the junctions as shown in the figure above.



Now let us see what happens if we apply a positive voltage at the base terminal of the device. In this situation, the base-emitter junction gets forward voltage individually and certainly, it can overcome the forward potential barrier and hence the majority carriers, i.e., free electrons in the emitter region will cross the junction and come in the base region where they get very few numbers of holes to recombine. But due to the electric field across the junction, the free electrons migrating from emitter region get kinetic energy. The base region is so thin that the free electrons coming from emitter do not get sufficient time to recombine and hence cross the reverse biased depletion region and ultimately come to the collector zone. As there is a reverse barrier present across the base-collector junction, it will not obstruct the flow of free electrons from the base to the collector as the free electrons in the base region are minority carriers.

In this way, electrons flow from emitter to collector and hence collector to emitter current starts flowing. As there are few holes present in the base region some of the electrons coming from emitter region will recombine with these holes and contribute base current. This base current is quite smaller than collector to emitter current. As some of the entire electrons migrating from emitter region contribute base current, rest major portion of them contribute current through the collector region. The current through emitter is called emitter current, the current through the collector is called collector current and the tiny current flowing through the base terminal is called base current. Hence here emitter current is the sum of base current and collector current.

Now let us increase the applied base voltage. In this situation due to the increased forward voltage across emitter-base junction proportionately more free electrons will come from the emitter region to the base region with more kinetic energy. This causes a proportionate increase of collector current. In this way, by controlling a small base signal, we can control quite a large collector signal. This is the basic working principle of a transistor.



A small current between the base and the Emitter controls a LARGE current between the Emitter and Collector

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Bipolar Junction Transistors

- Bipolar transistors have the ability to operate within three different regions:
  - Active Region: the transistor operates as an amplifier and $Ic = \beta * Ib$
  - Saturation: the transistor is “Fully-ON” operating as a switch and Ic = I(saturation)
  - Cut-off: the transistor is “Fully-OFF” operating as a switch and Ic = 0

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BJT Configurations

- **Common Base** – has Voltage Gain but no Current Gain.
- **Common Emitter** – has some Voltage and Current gain.
- **Common Collector** – has Current Gain but no Voltage Gain.

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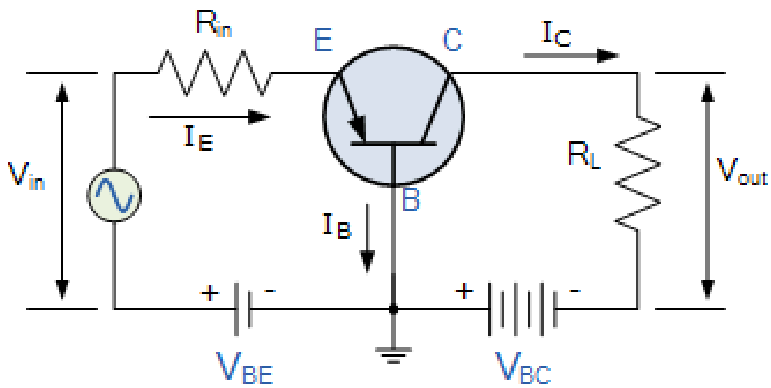
Common Base



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As its name suggests, in the **Common Base** or grounded base configuration, the BASE connection is common to both the input signal AND the output signal. The input signal is applied between the transistors base and the emitter terminals, while the corresponding output signal is taken from between the base and the collector terminals as shown. The base terminal is grounded or can be connected to some fixed reference voltage point.

The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a current gain for this type of circuit of “1” (unity) or less, in other words the common base configuration “attenuates” the input signal.

This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages Vin and Vout are “in-phase”. This type of transistor arrangement is not very common due to its unusually high voltage gain characteristics. Its input characteristics represent that of a forward biased diode while the output characteristics represent that of an illuminated photo-diode.

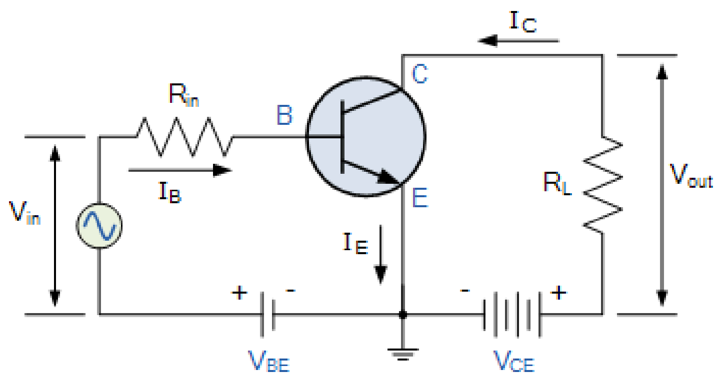
Also this type of bipolar transistor configuration has a high ratio of output to input resistance or more importantly “load” resistance (RL) to “input” resistance (Rin) giving it a value of “Resistance Gain”. Then the voltage gain (Av) for a common base configuration is therefore given as:

$$Av = \mathbf{Vout / Vin = (Ic \times Rl) / (Ie \times Rin)}$$

Where: Ic/Ie is the current gain, alpha (α) and RL/Rin is the resistance gain.

The common base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or radio frequency (Rf) amplifiers due to its very good high frequency response.

Common Emitter



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In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as Ie = Ic + Ib.

As the load resistance (R_L) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of Ic/Ib. A transistors current gain is given the Greek symbol of Beta, (β).

As the emitter current for a common emitter configuration is defined as Ie = Ic + Ib, the ratio of Ic/Ie is called Alpha, given the Greek symbol of α. Note: that the value of Alpha will always be less than unity.

Since the electrical relationship between these three currents, Ib, Ic and Ie is determined by the physical construction of the transistor itself, any small change in the base current (Ib), will result in a much larger change in the collector current (Ic).

Then, small changes in current flowing in the base will thus control the current in the emitter-collector circuit. Typically, Beta has a value between 20 and 200 for most general purpose transistors. So if a transistor has a Beta value of say 100, then one electron will flow from the base terminal for every 100 electrons flowing between the emitter-collector terminal.

By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the transistor can be given as:

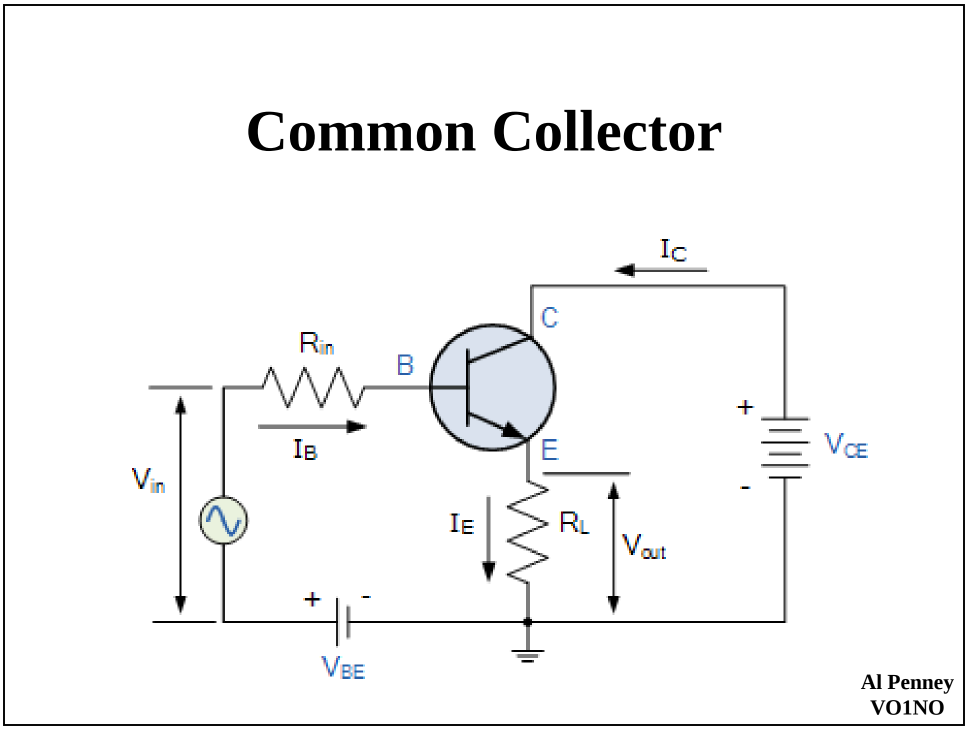
Alpha = Ic / Ie   Beta = Ic / I b

Alpha = Beta / (Beta + 1)   Beta = Alpha / (1 – Alpha)

Ie = Ic + Ib

Where: “Ic” is the current flowing into the collector terminal, “Ib” is the current flowing into the base terminal and “Ie” is the current flowing out of the emitter terminal.

Then to summarise a little. This type of bipolar transistor configuration has a greater input impedance, current and power gain than that of the common base configuration but its voltage gain is much lower. The common emitter configuration is an inverting amplifier circuit. This means that the resulting output signal has a 180^{o} phase-shift with regards to the input voltage signal.



The common emitter configuration has a current gain approximately equal to the β value of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current.

As the emitter current is the combination of the collector AND the base current combined, the load resistance in this type of transistor configuration also has both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

A = Bata + 1

This type of bipolar transistor configuration is a non-inverting circuit in that the signal voltages of Vin and Vout are “in-phase”. It has a voltage gain that is always less than “1” (unity). The load resistance of the common collector transistor receives both the base and collector currents giving a large current gain (as with the common emitter configuration) therefore, providing good current amplification with very little voltage gain.

Transistor Gain Parameters

- Gain of a transistor is a primary parameter.
- Specified in three different ways:
  - **Beta β**
  - **h_{FE}**
  - **h_{fe}**

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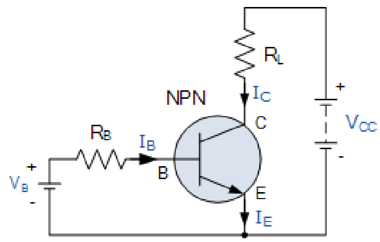
Beta β in NPN BJT



- Common Emitter mode
- DC current gain **β** = Output I / Input I
- Therefore **β** = **Ic / Ib**
- Typical value is 200
- Ie = Ib + Ic
- **Ic = β x Ib**
- Forward current gain in common emitter mode.
- Can also apply for common collector mode.
- **Change of collector current with respect to base current**

The construction and terminal voltages for a bipolar NPN transistor are shown above. The voltage between the Base and Emitter (V_{BE}), is positive at the Base and negative at the Emitter because for an NPN transistor, the Base terminal is always positive with respect to the Emitter. Also the Collector supply voltage is positive with respect to the Emitter (V_{CE}). So for a bipolar NPN transistor to conduct the Collector is always more positive with respect to both the Base and the Emitter.

Then the voltage sources are connected to an NPN transistor as shown. The Collector is connected to the supply voltage V_{CC} via the load resistor, RL which also acts to limit the maximum current flowing through the device. The Base supply voltage V_B is connected to the Base resistor R_B, which again is used to limit the maximum Base current.

So in a NPN Transistor it is the movement of negative current carriers (electrons) through the Base region that constitutes transistor action, since these mobile electrons provide the link between the Collector and Emitter circuits. This link between the input and output circuits is the main feature of transistor action because the transistors amplifying properties come from the consequent control which the Base exerts upon the Collector to Emitter current.

Then we can see that the transistor is a current operated device (Beta model) and that a large current (Ic) flows freely through the device between the collector and the emitter terminals when the transistor is switched "fully-ON". However, this only happens when a small biasing current (Ib) is flowing into the base terminal of the transistor at the same time thus allowing the Base to act as a sort of current control input.

The current in a bipolar NPN transistor is the ratio of these two currents (Ic/Ib), called the *DC Current Gain* of the device and is given the symbol of hfe or nowadays Beta, (β).

The value of β can be large up to 200 for standard transistors, and it is this large ratio between Ic and Ib that makes the bipolar NPN transistor a useful amplifying device when used in its active region as Ib provides the input and Ic provides the output. Note that Beta has no units as it is a ratio.

Also, the current gain of the transistor from the Collector terminal to the Emitter terminal, Ic/Ie, is called Alpha, (α), and is a function of the transistor itself (electrons diffusing across the junction). As the emitter current Ie is the sum of a very small base current plus a very large collector current, the value of alpha (α), is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 to 0.999

h_{fe}

- Current gain for a transistor expressed as an h parameter (hybrid parameter).
- Letter f indicates a forward transfer characteristic.
- Letter e indicates common emitter configuration.
- Small letter h indicates it is small signal AC gain.
- $h_{fe} = \Delta Ic / \Delta Ib$

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Transistor H_{fe}, h_{fe} are often seen quoted as the current gain. This can lead to some confusion.

The reason for using h_{fe} is that it refers to way of measuring the input and output parameters of a transistor.

However as a transistor exhibits a low input impedance and a high output impedance a form of parameter known as h or hybrid parameters are used.

h_{fe} is the forward transfer characteristic, i.e. transistor gain when used in the common emitter mode.

h_{fe} is exactly the same as the transistor Beta, β - it is just a little more correct to use it in datasheets.

h_{FE}

- The h_{FE} parameter differs from h_{fe} in that it is the h (hybrid) parameter for the DC or large signal steady state forward current gain.
- **h_{FE} = Ic / Ib**

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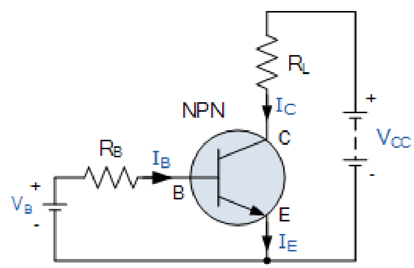
Alpha ά

- Ratio of change in Collector current to Emitter current.
- **$ά = \Delta Ic / \Delta Ie$**
- Value of **ά** must be less than 1, typically 0.950 to 0.999
- **$\beta = ά / (1 – ά)$**
- **$ά = \beta / (1 + \beta)$**



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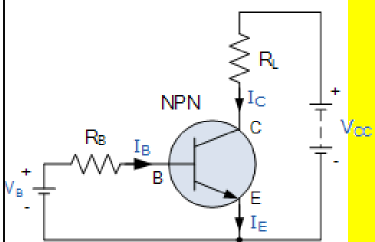

$$\text{DC Current Gain} = \frac{\text{Output Current}}{\text{Input Current}} = \frac{I_C}{I_B}$$

$$I_E = I_B + I_C \text{ ..... (KCL) and } \frac{I_C}{I_E} = \alpha$$

$$\text{Thus: } I_B = I_E - I_C$$

$$I_B = I_E - \alpha I_E$$

$$I_B = I_E(1-\alpha)$$

$$\therefore \beta = \frac{I_C}{I_B} = \frac{I_C}{I_E(1-\alpha)} = \frac{\alpha}{1-\alpha}$$

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$$\alpha = \frac{\beta}{\beta + 1} \quad \text{or} \quad \alpha = \beta(1 - \alpha)$$

$$\beta = \frac{\alpha}{1 - \alpha} \quad \text{or} \quad \beta = \alpha(1 + \beta)$$

If $\alpha = 0.99$ $\qquad \beta = \frac{0.99}{0.01} = 99$

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Transistor Characteristics

- **Breakdown Voltage**
  - Max voltage that may be safely applied to electrodes.
  - Symbol BV, with subscript indicating electrodes specified and state of 3rd electrode e.g.: BV_{CEO}

2N3904
BV_{CBO} =60Vdc
BV_{CEO} =40Vdc
BV_{EBO} =6Vdc

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The breakdown voltage ratings of a transistor are the maximum voltages that a transistor can handle for each of its 3 junctions. If voltages are fed to the transistor exceeding this rating, the transistor can be destroyed.

A datasheet for a transistor lists the breakdown voltage ratings for the emitter-base, collector-base, and collector-emitter junctions.

For example, a 2N3904 small signal transistor has the following breakdown voltage ratings:

BV_{CBO} =60 Vdc
BV_{CEO} =40 Vdc
BV_{EBO} =6 Vdc

The first 2 letters in the subscript indicate the two transistor terminals for which the voltage rating applies, and the third letter is in reference to the third unmentioned terminal which is left open.

The first voltage, BV_{CBO}, indicates the maximum allowable collector-to-base voltage with the emitter open. The second voltage, BV_{CEO}, is the maximum allowable collector-emitter voltage with the base open. The voltage rating, VEBO, is the maximum allowable emitter-base voltage with the collector open.

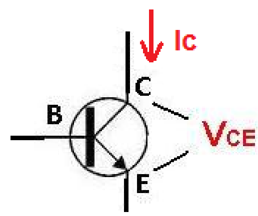
Exceeding any of these voltages can destroy the transistor.

Transistor Characteristics

- **Maximum Voltage**
  - Max operating voltages that may safely be applied to the electrodes.
  - Usually less than Breakdown Voltage, and never greater.
  - Uses same format as Breakdown Voltage, but V instead of BV.

Transistor Characteristics

- **Maximum Current** – Refers to the maximum continuous that can pass through the indicated terminal. The most important is Collector Current, I_c



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Transistor Characteristics

- **Maximum Power $P_{D\ max}$**
  - Maximum amount of power the device can shed in terms of heat.
  - Most heat dissipated in Collector circuit.
  - Rate of heat removal specified in temp rise per each watt of dissipated power e.g.: Deg/Watt
  - Cannot safely operate a transistor at max voltage and current!
  - Spec sheet has safe voltage/current curve.

The Power Dissipation Rating is the maximum power that a transistor can handle across its collector-emitter junction.

The power that is dissipated across this collector-emitter region depends on voltage, VCE, which is the voltage that drops across the collecter-emitter junction, and current, Ic, which is the current that flows across this junction. The product of VCE and IC makes up the power that is dissipated across the collector-emitter junction.

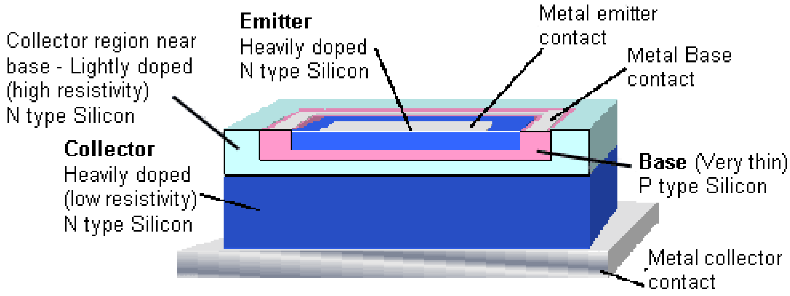
Pd= VCE X Ic

The product VCE X Ic must not exceed the maximum power dissipation rating, Pd(max), of the transistor.

Transistor Characteristics

- **Gain Bandwidth Product**
  - Current gain decreases as operating frequency increases.
  - **Gain Bandwidth fr** allows us to calculate gain that can be expected at different frequencies.
  - $\mathbf{F_T}$ is the frequency where gain is unity (where $h_{fe} = 1$).

Modern Bipolar Transistor



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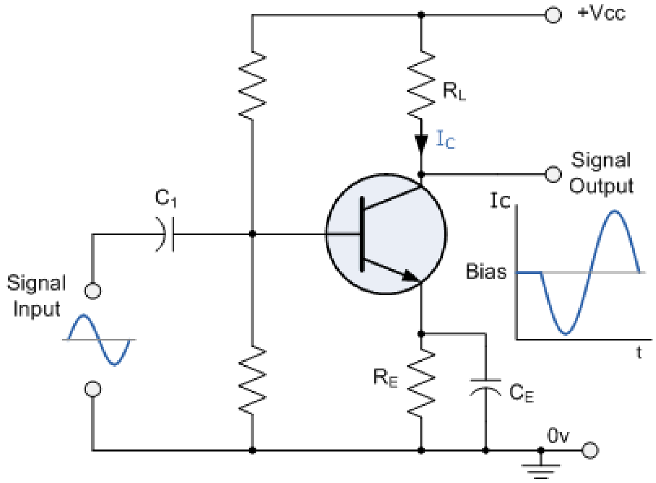
Basic Bipolar Transistor Amplifier



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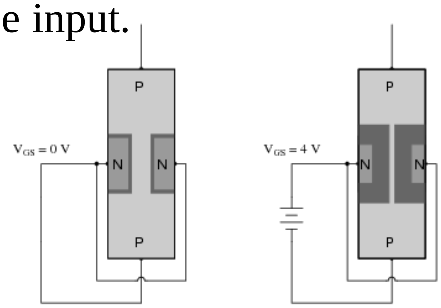
Field Effect Transistors

- Uses **voltage** to control the flow of current.
- Very little current flows through the Gate, so it does not affect the preceding circuit.
- Very high impedance input.



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The **field-effect transistor** (FET) is a transistor that uses an electric field to control the shape and hence the conductivity of a channel of one type of charge carrier in a semiconductor material. FETs are unipolar transistors as they involve single-carrier-type operation. The *concept* of the FET predates the bipolar junction transistor (BJT), though it was not physically implemented until *after* BJTs due to the limitations of semiconductor materials and the relative ease of manufacturing BJTs compared to FETs at the time.

The field-effect transistor was first patented by Julius Edgar Lilienfeld in 1926 and by Oskar Heil in 1934, but practical semiconducting devices (the JFET) were developed only much later after the transistor effect was observed and explained by the team of William Shockley at Bell Labs in 1947. The MOSFET, which largely superseded the JFET and had a more profound effect on electronic development, was invented by Dawon Kahng and Martin Atalla in 1960.

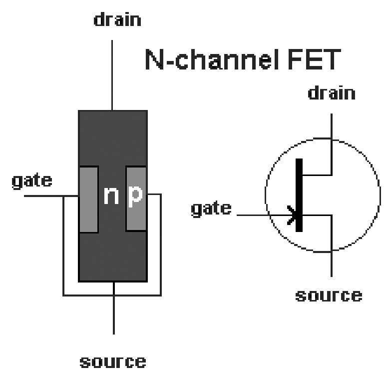
The main advantage of the FET is its high input resistance, on the order of 100 MΩ or more. Thus, it is a voltage-controlled device, and shows a high degree of isolation between input and output. It is a unipolar device, depending only on majority current flow. Because base current noise will increase with shaping time, a FET typically produces less noise than a bipolar junction transistor (BJT), and is thus found in noise sensitive electronics such as tuners and low-noise amplifiers for VHF and satellite receivers. It is relatively immune to radiation. It exhibits no offset voltage at zero drain current and hence makes an excellent signal chopper. It typically has better thermal stability than a BJT.[3]

Disadvantages of FET

It has a relatively low gain-bandwidth product compared to a BJT. The MOSFET has a drawback of being very susceptible to overload voltages, thus requiring special handling during installation. The fragile insulating layer of the MOSFET between the gate and channel makes it vulnerable to electrostatic damage during handling. This is not usually a problem after the device has been installed in a properly designed circuit.

Field Effect Transistors

- **Source** – Terminal where the charge carriers enter the channel.
- **Drain** – Terminal where charge carriers exit the channel.
- **Gate** – Electrode that controls the conductance of the channel between the Source and Drain.



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Types of FETs

- The **JFET** (Junction Field Effect Transistor) uses a reverse biased P-N junction to separate the gate from the body.
- The **MOSFET** (Metal Oxide Semiconductor Field Effect Transistor) utilizes an insulator (typically SiO_2 - glass) between the gate and the body.

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The FET transistors have high input impedance where as BJT has relatively low. Due to this high impedance values the FET transistors are very sensitive to small input voltages. The FET transistors are mainly classified into two types; they are Junction Field Effect Transistor (JFET) and Insulated Gate FET (IG-FET) or Metal Oxide Semiconductor FET (MOSFET).

The Junction Field Effect transistor (JFET) is one of the types of FET transistors. JFET is a simplest form of FET transistors and it has three terminals. The JFET transistors are used as electronically controlled switches, Voltage controlled resistors and as amplifiers.

The JFET transistors are classified into two types; they are N-channel JFET and P-channel JFET. In the N-channel JFET the channel is doped with the donor impurities due to this the current passing through the channel is negative (i.e. due to electrons) but in the P-channel JFETs the channel is doped with the acceptor impurities due to this the current flowing through this channel is positive (i.e. due to holes).

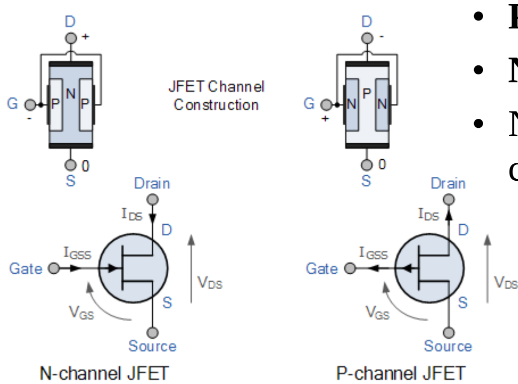
The N-channel JFET has more current conduction than P-channel JFET because the mobility of electrons is greater than the mobility of holes. So the N-channel JFETs are widely used than P-channel JFETs.

The small voltage at the gate (G) terminal controls the current flow in the channel (between drain and source) of the JFET.

Metal Oxide Semiconductor FET

The Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is one type of FET transistor. In these transistors the gate terminal is electrically insulated from the current carrying channel so that it is also called as Insulated Gate FET (IG-FET). Due to the insulation between gate and source terminals the input resistance of MOSFET may be very high such as in mega ohms (MΩ).

N and P Channel JFET



- **P Channel uses holes**.
- **N Channel uses electrons**.
- N Channel have lower channel resistance.

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There are two basic configurations of junction field effect transistor, the N-channel JFET and the P-channel JFET. The N-channel JFET's channel is doped with donor impurities meaning that the flow of current through the channel is negative (hence the term N-channel) in the form of electrons.

Likewise, the P-channel JFET's channel is doped with acceptor impurities meaning that the flow of current through the channel is positive (hence the term P-channel) in the form of holes. N-channel JFET's have a greater channel conductivity (lower resistance) than their equivalent P-channel types, since electrons have a higher mobility through a conductor compared to holes. This makes the N-channel JFET's a more efficient conductor compared to their P-channel counterparts.

MOSFET

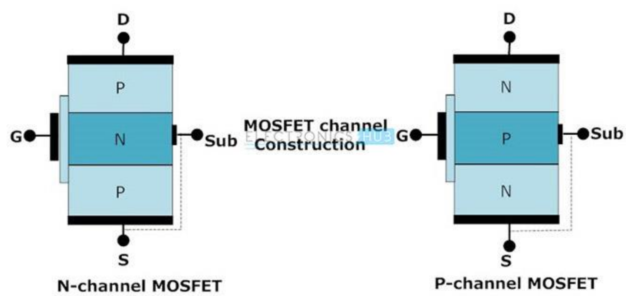
- **Gate** terminal is electrically **insulated** from the current carrying channel.
- Also called as Insulated Gate FET (**IG-FET**).
- Input resistance of MOSFET in **mega ohms** (MΩ).
- In addition to Gate, Source and Drain, MOSFETS have additional terminal called **Substrate, or Body**.
- MOSFETS are basis of modern electronics – more than 13 sextillion made (**1.3 x 10^{22}**) made since 1960.

MOSFETs are the basic building block of modern electronics, and the most widely manufactured device in history, with an estimated total of 13 sextillion (1.3 × 10^{22}) MOSFETs manufactured between 1960 and 2018.

The MOSFET is the most common semiconductor device in digital and analog circuits. It was the first truly compact transistor that could be miniaturised and mass-produced for a wide range of uses, revolutionizing the electronics industry and the world economy, having been central to the computer revolution, digital revolution, information revolution, silicon age and information age. MOSFET scaling and miniaturization has been driving the rapid exponential growth of electronic semiconductor technology since the 1960s. MOSFETs enable high-density integrated circuits (ICs) such as memory chips and microprocessors, and are the most common power devices. MOSFETs are used for many applications, such as amplifiers, audio equipment, automotives, biosensors, cameras, calculators, computers, consumer electronics, home entertainment, industrial equipment, the Internet, LED lighting, mobile devices, power electronics, power supplies, 3D printers, satellites, spacecraft, telecommunication, television, video games, watches, wireless networks, and X-ray, among other uses. The MOSFET is considered to be possibly the most important invention in electronics, and the USPTO calls it a "groundbreaking invention that transformed life and culture around the world".

MOSFET

- Gate potential measured relative to substrate.
- Substrate connected to Source to ensure consistent behaviour.



The gate voltage modifies the channel width. But the gate potential is measured relative to the **substrate** potential, and the channel is formed in the **substrate** material. Therefore the **MOSFET** behavior depends strongly on the **substrate** (**body**) potential. ... We **connect** to the **body** to take control of this behavior

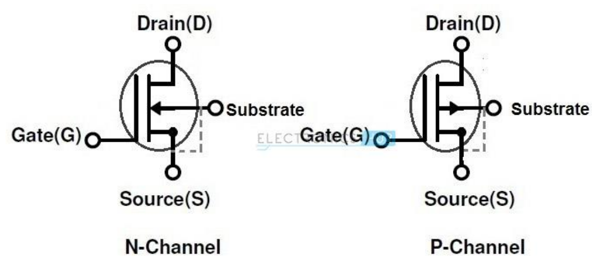
The **IGFET** or **MOSFET** is a voltage controlled field effect transistor that differs from a JFET in that it has a "Metal Oxide" Gate electrode which is electrically insulated from the main semiconductor n-channel or p-channel by a very thin layer of insulating material usually silicon dioxide, commonly known as glass.

This ultra thin insulated metal gate electrode can be thought of as one plate of a capacitor. The isolation of the controlling Gate makes the input resistance of the **MOSFET** extremely high way up in the Mega-ohms (MΩ) region thereby making it almost infinite.

As the Gate terminal is electrically isolated from the main current carrying channel between the drain and source, "NO current flows into the gate" and just like the JFET, the MOSFET also acts like a voltage controlled resistor where the current flowing through the main channel between the Drain and Source is proportional to the input voltage. Also like the JFET, the MOSFETs very high input resistance can easily accumulate large amounts of static charge resulting in the **MOSFET** becoming easily damaged unless carefully handled or protected.

Depletion Type MOSFET

- Equivalent to "**Normally Closed**" (on) switch.
- Requires Gate-Source voltage to switch off.
- Note **continuous thick line** between Drain and Source represents Depletion Type.



Depletion Type

The depletion type MOSFET transistor is equivalent to a "normally closed" switch. The depletion type of transistors requires gate – source voltage (V_{GS}) to switch OFF the device.

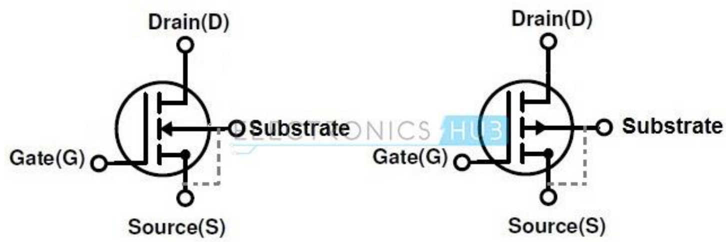
The symbols for depletion mode of MOSFETs in both N-channel and P-channel types are shown above. In the above symbols we can observe that the fourth terminal substrate is connected to the ground, but in discrete MOSFETs it is connected to source terminal. The continuous thick line connected between the drain and source terminal represents the depletion type. The arrow symbol indicates the type of channel, such as N-channel or P-channel. In this type of MOSFETs a thin layer of silicon is deposited below the gate terminal. The depletion mode MOSFET transistors are generally ON at zero gate-source voltage (V_{GS}). The conductivity of the channel in depletion MOSFETs is less compared to the enhancement type of MOSFETs.

Depletion Type MOSFET

- Electron conduction in an N-channel depletion type MOSFET is associated with N-channel depletion.
- Hole conduction in a P-channel depletion type MOSFET is associated with P-channel depletion.

Enhancement Type MOSFET

- Equivalent to "**Normally Open**" (off) switch.
- Require Gate-Source voltage to switch on.
- Note **broken thick line** between Drain and Source represents Enhancement Type.



Enhancement Type

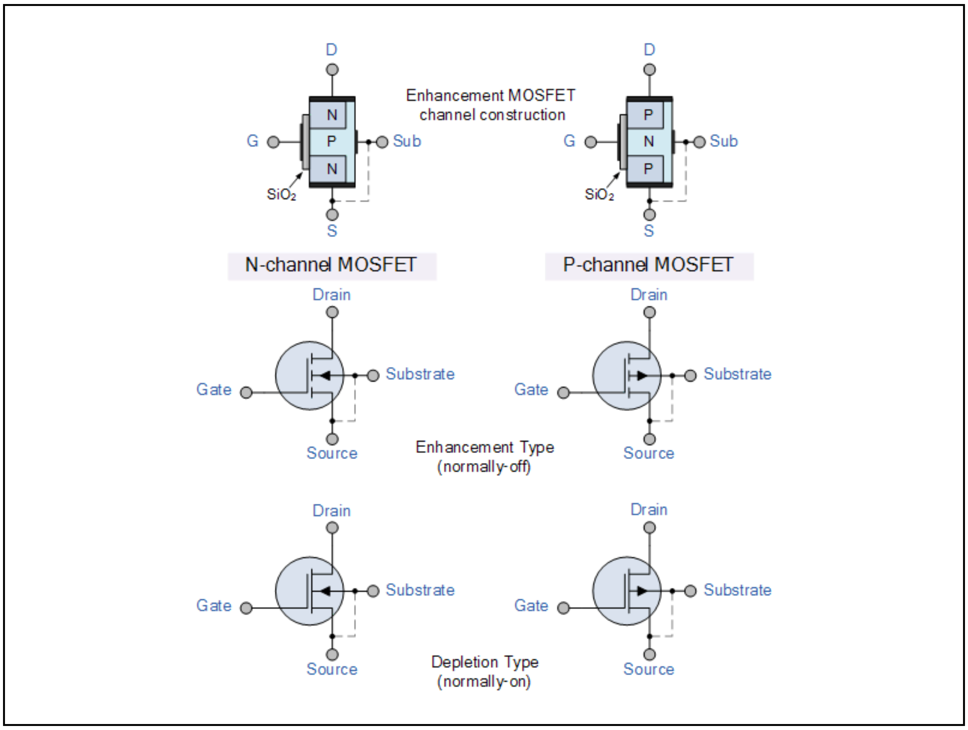
The Enhancement mode MOSFET is equivalent to "Normally Open" switch and these types of transistors require gate-source voltage to switch ON the device. The symbols of both N-channel and P-channel enhancement mode MOSFET transistors are shown below.

Here we can observe that the broken line is connected between the source and drain which represents the enhancement mode type. In enhancement mode MOSFETs the conductivity increases by increasing the oxide layer which adds the carriers to the channel.

Generally, this oxide layer is called as 'Inversion layer'. The channel is formed between the drain and source in the opposite type to the substrate, such as N-channel is made with a P-type substrate and P-channel is made with an N-type substrate. The conductivity of the channel due to electrons or holes depends on N-type or P-type channel respectively.

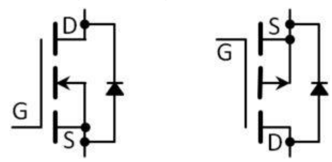
Enhancement Type MOSFET

- Electron conduction in an N-channel enhancement MOSFET is associated with N-channel enhancement.
- Hole conduction in a P-channel enhancement type MOSFET is associated with P-channel enhancement.


D
Enhancement MOSFET
channel construction
N
P
N
G
Sub
SiO2
S
D
P
N
P
G
Sub
SiO2
S
N-channel MOSFET
P-channel MOSFET
Drain
Gate
Substrate
Source
Enhancement Type
(normally-off)
Drain
Gate
Substrate
Source
Drain
Gate
Substrate
Source
Depletion Type
(normally-on)
Drain
Gate
Substrate
Source

Static Protection

- MOSFETs have much higher input impedance than JFETs.
- Much more susceptible to static electricity.
- Observe static precautions when handling MOSFETS, CMOS etc.
- MOSFETS have built-in diodes for protection against **static puncturing the gate insulation**.



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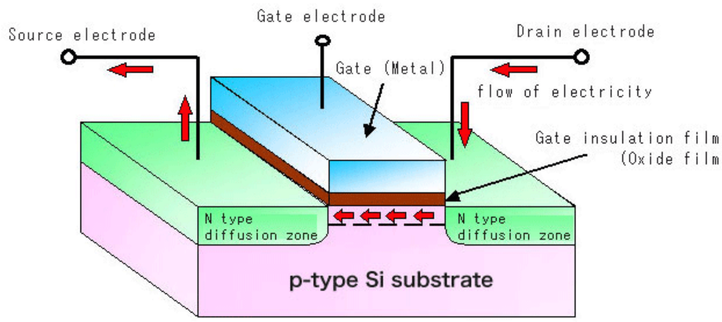
The **Freewheel diode** is used to protect solid state switches such as power transistors and MOSFET's from damage by reverse battery protection as well as protection from highly inductive loads such as relay coils or motors, and an example of its connection is shown below.

Modern fast switching, power semiconductor devices require fast switching diodes such as free wheeling diodes to protect them form inductive loads such as motor coils or relay windings. Every time the switching device above is turned "ON", the freewheel diode changes from a conducting state to a blocking state as it becomes reversed biased.

However, when the device rapidly turns "OFF", the diode becomes forward biased and the collapse of the energy stored in the coil causes a current to flow through the freewheel diode. Without the protection of the freewheel diode high di/dt currents would occur causing a high voltage spike or transient to flow around the circuit possibly damaging the switching device.

MOSFET



Construction of MOSFET

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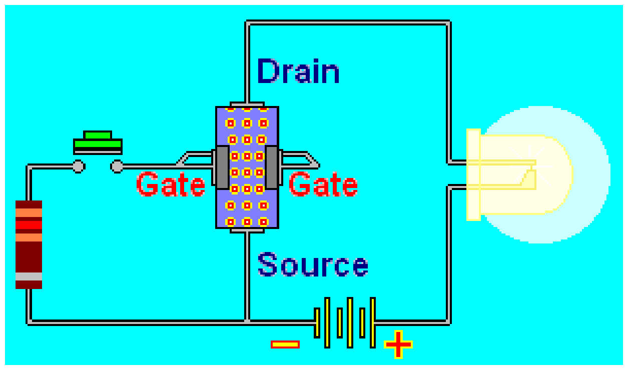
The construction of the Metal Oxide Semiconductor FET is very different to that of the Junction FET. Both the Depletion and Enhancement type MOSFETs use an electrical field produced by a gate voltage to alter the flow of charge carriers, electrons for n-channel or holes for P-channel, through the semiconductive drain-source channel. The gate electrode is placed on top of a very thin insulating layer and there are a pair of small n-type regions just under the drain and source electrodes.

We saw in the previous tutorial, that the gate of a junction field effect transistor, JFET must be biased in such a way as to reverse-bias the pn-junction. With a insulated gate MOSFET device no such limitations apply so it is possible to bias the gate of a MOSFET in either polarity, positive (+ve) or negative (-ve).

This makes the MOSFET device especially valuable as electronic switches or to make logic gates because with no bias they are normally non-conducting and this high gate input resistance means that very little or no control current is needed as MOSFETs are voltage controlled devices. Both the p-channel and the n-channel MOSFETs are available in two basic forms, the **Enhancement** type and the **Depletion** type.

Pinch-Off Voltage

- The reverse bias voltage that cuts off conduction completely.



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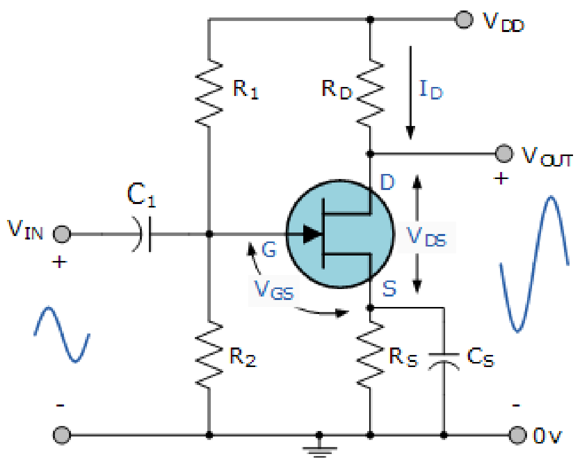
Basic FET Amplifier



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Thyristors

- Bistable switches that conduct when the gate receives a current trigger, and continue to conduct until the voltage across the device is reversed biased, or until the voltage is removed by some other means.
- Four-layer solid-state current-controlling devices: **P-N-P-N**.
- Includes a wide variety of devices, including SCR, TRIACS, UJTs, etc.

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The thyristor may be considered a rather an unusual form of electronics component because it consists of four layers of differently doped silicon rather than the three layers of the conventional bipolar transistors.

Whereas conventional bipolar transistors may have a p-n-p or n-p-n structure with the electrodes named collector, base and emitter, the thyristor has a p-n-p-n structure with the outer layers with their electrodes referred to as the anode (n-type) and the cathode (p-type). The control terminal of the SCR is named the gate and it is connected to the p-type layer that adjoins the cathode layer.

Thyristors, or silicon controlled rectifiers, SCRs are used in many areas of electronics where they find uses in a variety of different applications. Some of the more common applications for them are outlined below:

•AC power control (including lights, motors,etc).

•AC power electronic switching.

•Overvoltage protection crowbar for power supplies.

•Control elements in phase angle triggered controllers.

•Within photographic flash lights where they act as the electronic switch to discharge a stored voltage through the flash lamp, and then cut it off at the required time.

Thyristors are able to switch high voltages and withstand reverse voltages making them ideal for electronic switching applications, especially within AC scenarios.

Silicon Controlled Rectifier (SCR)

- Three terminals:
  - **Anode**: Positive terminal
  - **Cathode**: Negative terminal
  - **Gate: Used to control the device**
- Acts like a **forward-biased normal silicon rectifier diode** ONLY if positive pulse applied to Gate.
- Once activated, it acts like a switch in the "ON" position.
- Once "ON", it will remain "ON" until external circuit reduces anode voltage to below value needed to maintain the gate open.

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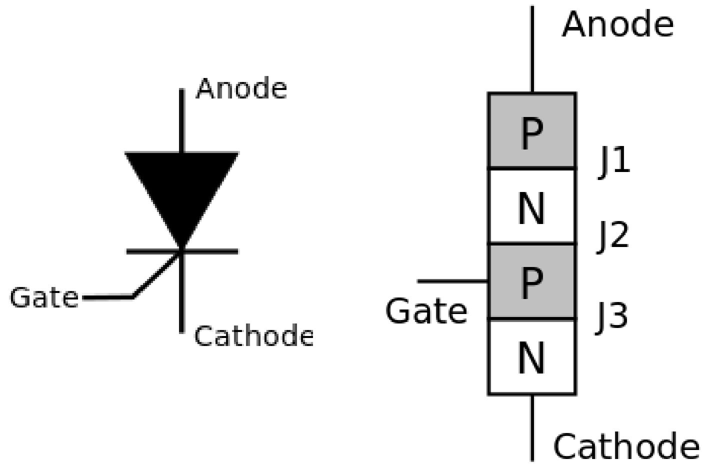
The way in which a thyristor operates is different to other devices. Normally no current flows across the device. However if a supply is connected across the device, and a small amount of current is injected into the gate, then the device will "fire" and conduct. It will remain in the conducting state until the supply is removed.

Silicon Controlled Rectifier (SCR)



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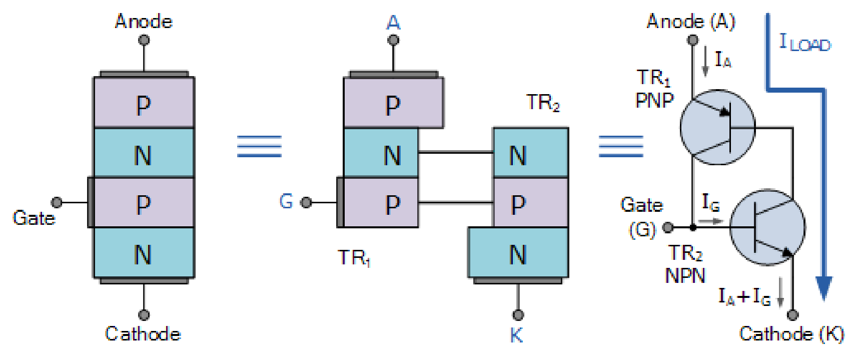
Silicon Controlled Rectifier (SCR)

- Two stable operating conditions:
  - **Conducting**; and
  - **Non-Conducting**.
- In Amateur Radio, SCRs usually used for **over-voltage crowbar protection** circuits.

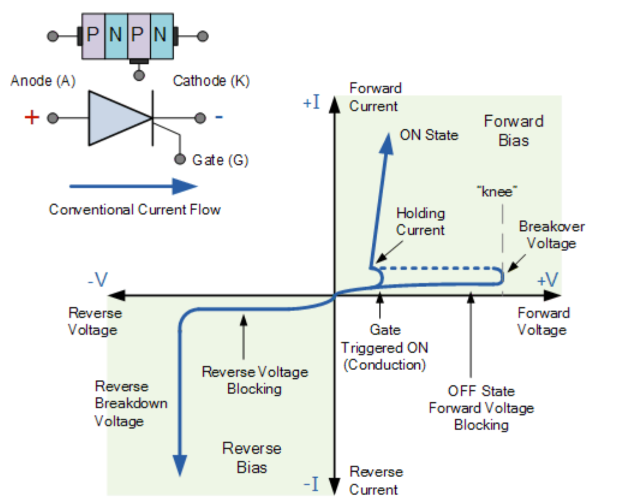
SCR Transistor Equivalent



The two transistor equivalent circuit shows that the collector current of the NPN transistor TR_2 feeds directly into the base of the PNP transistor TR_1, while the collector current of TR_1 feeds into the base of TR_2. These two inter-connected transistors rely upon each other for conduction as each transistor gets its base-emitter current from the other's collector-emitter current. So until one of the transistors is given some base current nothing can happen even if an Anode-to-Cathode voltage is present.

When the thyristors Anode terminal is negative with respect to the Cathode, the centre *N-P* junction is forward biased, but the two outer *P-N* junctions are reversed biased and it behaves very much like an ordinary diode. Therefore a thyristor blocks the flow of reverse current until at some high voltage level the breakdown voltage point of the two outer junctions is exceeded and the thyristor conducts without the application of a Gate signal.

SCR Voltage



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Once triggered into conduction, the current flowing through the device between the Anode and the Cathode is limited only by the resistance of the external circuit as the forward resistance of the device when conducting can be very low at less than 1Ω so the voltage drop across it and power loss is also low.

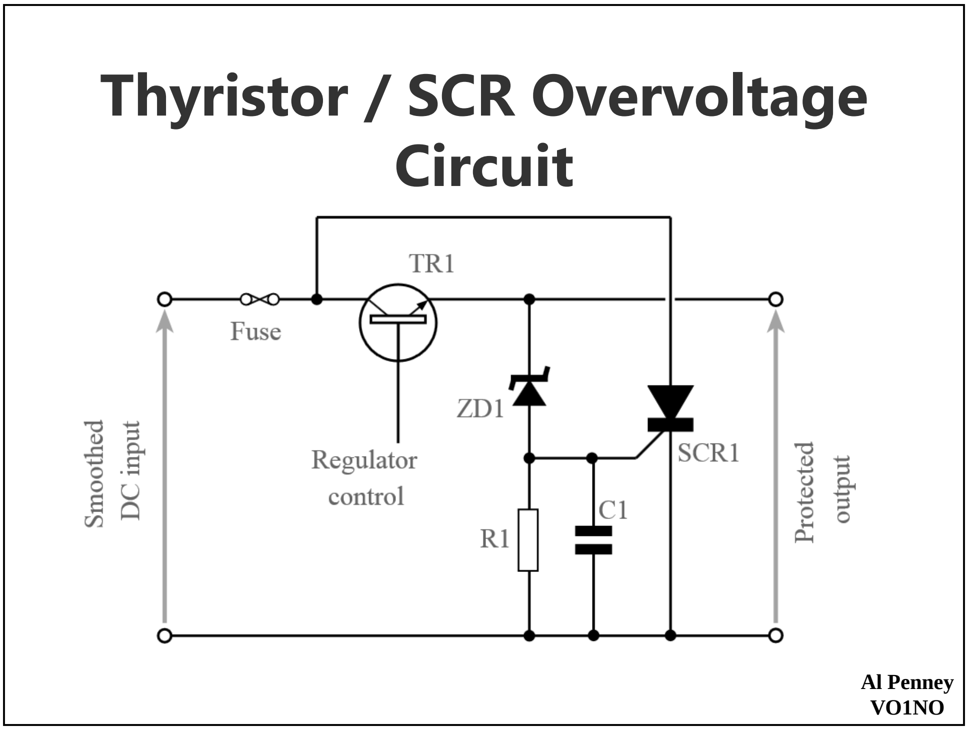
Then we can see that a thyristor blocks current in both directions of an AC supply in its “OFF” state and can be turned “ON” and made to act like a normal rectifying diode by the application of a positive current to the “Gate” terminal.

The operating voltage-current **I-V** characteristics curves for the operation of a **Silicon Controlled Rectifier** are given above:

Once the thyristor has been turned “ON” and is passing current in the forward direction (anode positive), the gate signal looses all control due to the regenerative latching action of the two internal transistors. The application of any gate signals or pulses after regeneration is initiated will have no effect at all because the thyristor is already conducting and fully-ON.

Unlike the transistor, the SCR can not be biased to stay within some active region along a load line between its blocking and saturation states. The magnitude and duration of the gate “turn-on” pulse has little effect on the operation of the device since conduction is controlled internally. Then applying a momentary gate pulse to the device is enough to cause it to conduct and will remain permanently “ON” even if the gate signal is completely removed.

Therefore the thyristor can also be thought of as a *Bistable Latch* having two stable states “OFF” or “ON”. This is because with no gate signal applied, a silicon controlled rectifier blocks current in both directions of an AC waveform, and once it is triggered into conduction, the regenerative latching action means that it cannot be turned “OFF” again just by using its Gate.



It uses just four components: a silicon controlled rectifier or SCR, a zener diode, a resistor and a capacitor.

As a silicon controlled rectifier, SCR, or thyristor is able to carry a relatively high current - even quite average devices can conduct five amps and short current peaks of may be 50 and more amps, cheap devices can provide a very good level of protection for small cost. Also voltage across the SCR will be low, typically only a volt when it has fired and as a result the heat sinking is not a problem.

The small resistor, often around 100 ohms from the gate of the thyristor or SCR to ground is required so that the Zener can supply a reasonable current when it turns on. It also clamps the gate voltage at ground potential until the Zener turns on. The capacitor C1 is present to ensure that short spikes to not trigger the circuit. Some optimisation may be required in choosing the correct value although 0.1 microfarads is a good starting point.

If the power supply is to be used with radio transmitters, the filtering on the input to the gate may need to be a little more sophisticated, otherwise RF from the transmitter may get onto the gate and cause false triggering. The capacitor C1 will need to be present, but a small amount of inductance may also help. A ferrite bead may even be sufficient. Experimentation to ensure that the time delay for the thyristor to trigger is not too long against removing the RF. Filtering on the power line to / from the transmitter can also help.

Although this power supply overvoltage protection circuit is widely used, it does have some limitations.

•***Crowbar firing voltage:*** The firing voltage of the tthyristor crowbar circuit is set by the Zener diode. It is necessary to chose a Zener diode with the right voltage . Zener diodes are not adjustable, and they come with at best a 5% tolerance. The firing voltage must be sufficiently far above the nominal power supply output voltage to ensure that any spikes that may appear on the line do not fire the circuit.

•***Susceptibility to RF:*** If the power supply is to be used to power a transmitter filtering on the line to / from the transmitter is required along with some careful design of the spike protection on the gate.

•***Circuit threshold :*** When taking into account all the tolerances and margins the guaranteed voltage at which the circuit may fire can be 20 - 40% above the nominal dependent upon the voltage of the power supply. The lower the voltage the greater the margins needed. Often on a 5 volt supply there can be difficulty designing it so that the overvoltage crowbar fires below 7 volts where damage may be caused to circuits being protected.

Darlington Pair

- Multi-transistor configuration made by two bipolar transistors connected such that the current amplified by the first transistor is amplified further by the second one.
- Gives a much **higher current gain** than each transistor taken separately.

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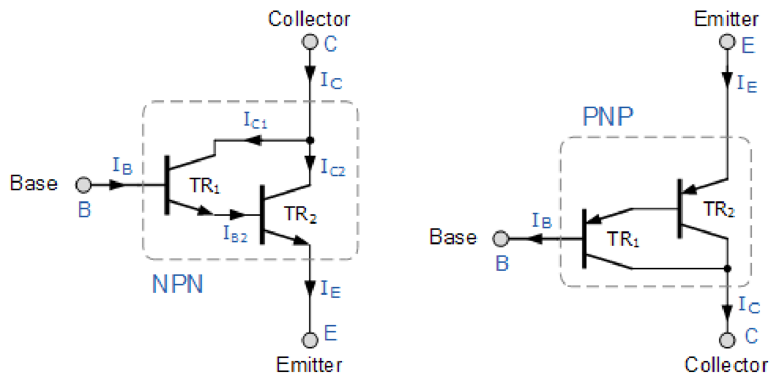
The ratio of collector current to base current (β) is known as the *current gain* of the transistor. A typical value of β for a standard bipolar transistor may be in the range of 50 to 200 and varies even between transistors of the same part number. In some cases where the current gain of a single transistor is too low to directly drive a load, one way to increase the gain is to use a Darlington pair.

Darlington Pair



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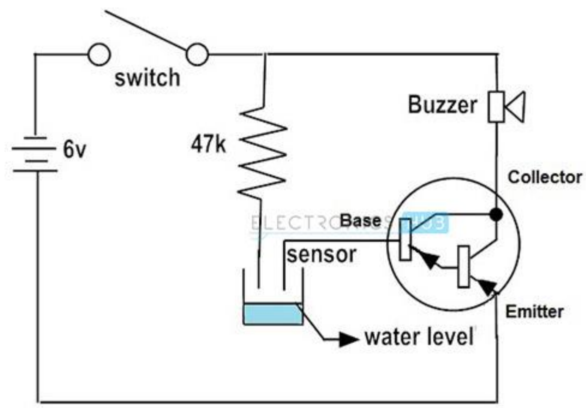
A **Darlington Transistor** configuration, also known as a "Darlington pair" or "super-alpha circuit", consist of two NPN or PNP transistors connected together so that the emitter current of the first transistor TR_1 becomes the base current of the second transistor TR_2. Then transistor TR1 is connected as an emitter follower and TR2 as a common emitter amplifier as shown above.

Also note that in this Darlington pair configuration, the collector current of the slave or control transistor, TR1 is "in-phase" with that of the master switching transistor TR2.

A Darlington pair behaves like a single transistor, meaning it has one base, collector, and emitter. It typically creates a high current gain (approximately the product of the gains of the two transistors, due to the fact that their β values multiply together).

The overall current gain, β is given by the gain of the first transistor multiplied by the gain of the second transistor as the current gains of the two transistors multiply. In other words, a pair of bipolar transistors combined together to make a single Darlington transistor pair can be regarded as a single transistor with a very high value of β and consequently a high input resistance.

Darlington Pair Applications



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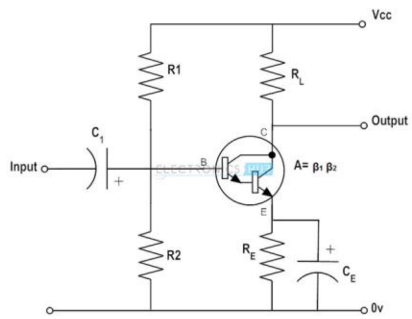
Darlington transistors are mainly used in switching and amplification applications for delivering a very high DC current gain. Some of the key applications are high and low side switches, sensor amplifiers and audio amplifiers. For light-sensitive applications photodarlingtons are used. Let us look at the operation of a Darlington transistor for a specific application.

•This circuit is a simple water level indicator wherein Darlington pair is used as a switch. We know that this transistor configuration provides a large collector current so it is able drive the buzzer at the output.

•When the water level is not enough to close the sensor, Darlington transistor is in OFF state. Therefore, the circuit becomes open and no current flows through it.

•As the water level increases, sensor become active and gives a necessary base current to the Darlington pair. Therefore, the circuit becomes short and load current flows so that the buzzer gives an alarm or sound.

Darlington Pair Applications



- As an audio amp, Darlington Pair offers:
  - High gain;
  - High input impedance; and
  - Low output impedance.

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Darlington Transistor as Amplifier

In case of power or voltage amplifiers the load resistance at the output is very low to have high current flow. This current flows through the collector terminal of a transistor if transistor is used for amplification. To be capable to suit for power amplifiers, transistors must drive high load currents.

This requirement may not be possible with single transistor that driven by a small base current. To meet the high load current requirement, the Darlington pair is used which offers a high current gain.

Above figure shows a class A amplifier circuit that uses a Darlington transistor configuration to have a high collector current. Darlington transistor offers a gain that equal to the product of two individual gains.

Therefore, with a small base current, the output current at the collector terminal is very high. So with the arrangement of Darlington transistor, this amplifier provides enough amplified current to the load.

Advantages of Darlington Pair

Darlington pair has several advantages as compared with standard single transistor. Some of them are

- It produces a very high current gain than standard single transistor
- It offers a very High input impedance or good impedance transformation that it can alter a high impedance input or source to low impedance load.
- These can be made by two separate transistors or comes with a single package.
- Easy and convenient circuit configuration as few components are used.
- In case of photo-Darlington pair, noise introduced is very less compared with phototransistor with an external amplifier.

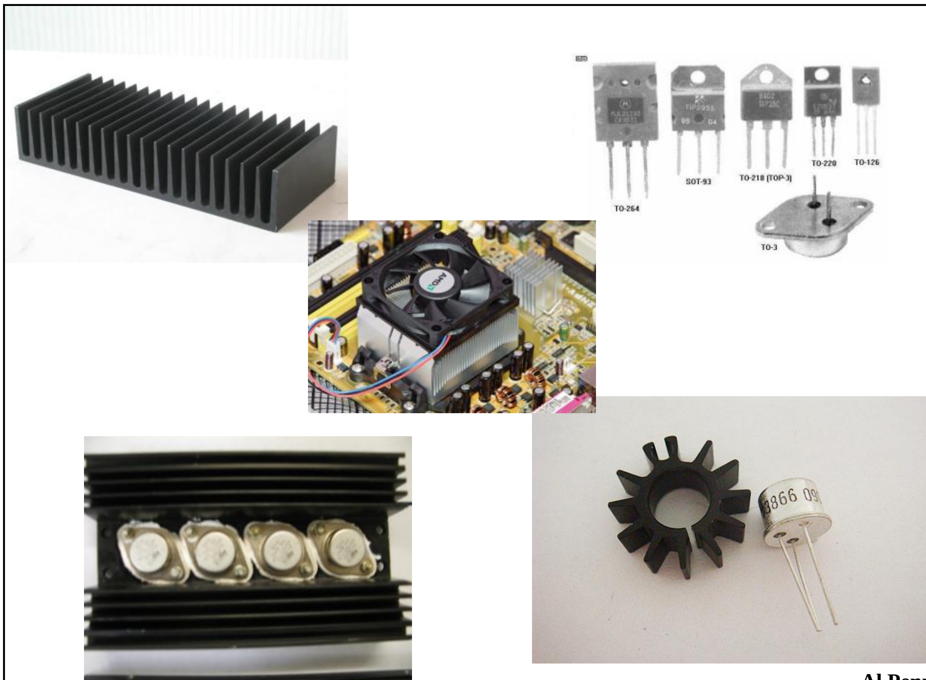
Disadvantages of Darlington Transistor

- Switching speed is low
- Bandwidth is limited
- At certain frequencies in negative feedback circuit, this configuration introduces a phase shift.
- The base-emitter voltage required is high and is two times the single standard transistor.
- High power dissipation due to high saturation voltage.
- The overall leakage current is high because the leakage current of the first transistor is amplified by the next transistor. That's why the three or more stages of Darlington is impossible.

Heat – Semiconductors' Enemy!

- Junctions in semiconductor devices are small, but where heat is produced.
- Junction temp limits max forward current.
- Silicon transistors – max 200 deg C
- Germanium transistors – max 85–100 deg C.
- Greater junction temp allows greater Collector current, causing more heat, and even greater current.
- Leads to **thermal runaway**, and eventual destruction of the device.

The leakage current Icbo is extremely temperature dependent and increases with the rise in temperature of collector-base junction. With the increase in collector current Ic, collector power dissipation increases which raises the junction temperature that leads to further increase in collector current Ic. The process is cumulative and may lead to the eventual destruction of transistor. **This phenomenon is known as THERMAL RUNAWAY** of transistor. In practice the Thermal Runaway can be prevented by a well designed circuit called as **STABILIZATION Circuitry.**



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When the power dissipation at the collector-base junction of a transistor is small, as in case of a small signal transistor, the surface area of the transistor case is normally large enough to allow all of the heat to escape. But for the large power dissipation that can occur in high power transistor the transistor surface area is not enough and junction temperature may rise to a dangerous level. However, power handling capacity of a transistor can be increased by making suitable provision for rapid conduction of heat away from the transistor junction. This is achieved by selecting a sheet of metal called the **HEAT SINK** which increases the area of contact with the atmosphere.

Heat

- Ambient temperature is **25 deg C**.
- Remember that power handling capacity of semiconductors decreases at ambient temperature increases – less ability to dissipate heat.
- Review calculations in handbook to determine heatsink requirements.
- Don’t forget thermal grease, airflow etc.
- Always err on the side of extra heat dissipation!

Questions?

Vacuum Tubes

- An electronic device that controls electric current through a vacuum in a sealed container.
- Obsolete now, but still used for some specialized applications.
- Often found in power amplifiers ("Linears").

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In electronics, a **vacuum tube**, **electron tube** (in North America), **tube**, or **thermionic valve** or **valve** (in British English) is a device controlling electric current through a vacuum in a sealed container. The simplest vacuum tube, the diode, contains only two elements; current can only flow in one direction through the device between the two electrodes, as electrons emitted by the hot cathode travel through the tube and are collected by the anode. Addition of a third and additional electrodes allows the current flowing between cathode and anode to be controlled in various ways.[1] The device can be used as an electronic amplifier, a rectifier, an electronically controlled switch, an oscillator, and for other purposes.

Vacuum tubes mostly rely on thermionic emission of electrons from a hot filament or a cathode heated by the filament. Some electron tube devices rely on the properties of a discharge through an ionized gas.

Vacuum tubes were critical to the development of electronic technology, which drove the expansion and commercialization of radio broadcasting, television, radar, sound reinforcement, sound recording and reproduction, large telephone networks, analog and digital computers, and industrial process control. Although some applications had counterparts using earlier technologies such as the spark gap transmitter or mechanical computers, it was the invention of the vacuum tube with three electrodes (called a *triode*) and its capability of electronic amplification that made these technologies widespread and practical.

In most applications, solid-state devices such as transistors and other semiconductor devices have replaced tubes. Solid-state devices last longer and are smaller, more efficient, more reliable, and cheaper than tubes. However, tubes are still manufactured for applications where solid-state devices are impractical.

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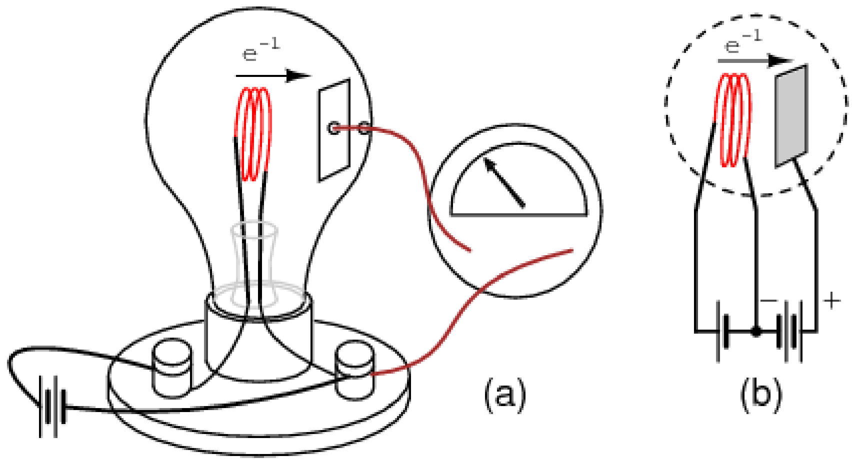
Edison Effect



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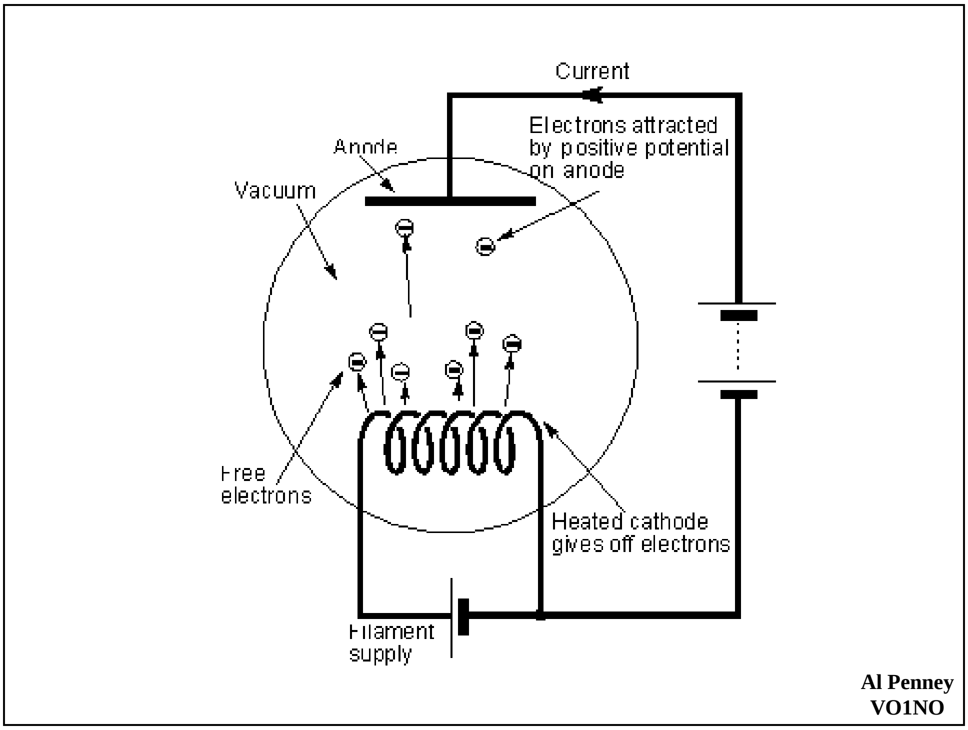
Thermionic emission is the heat-induced flow of charge carriers from a surface or over a potential-energy barrier. This occurs because the thermal energy given to the carrier overcomes the binding potential, also known as work function of the metal. The charge carriers can be electrons or ions, and in older literature are sometimes referred to as "thermions". After emission, a charge will initially be left behind in the emitting region that is equal in magnitude and opposite in sign to the total charge emitted. But if the emitter is connected to a battery, then this charge left behind will be neutralized by charge supplied by the battery, as the emitted charge carriers move away from the emitter, and finally the emitter will be in the same state as it was before emission. The thermionic emission of electrons is also known as *thermal electron emission.*

The classical example of thermionic emission is the emission of electrons from a hot cathode into a vacuum (also known as the **Edison effect**) in a vacuum tube. The hot cathode can be a metal filament, a coated metal filament, or a separate structure of metal or carbides or borides of transition metals. Vacuum emission from metals tends to become significant only for temperatures over 1000 K. The science dealing with this phenomenon has been known as **thermionics**, but this name seems to be gradually falling into disuse.

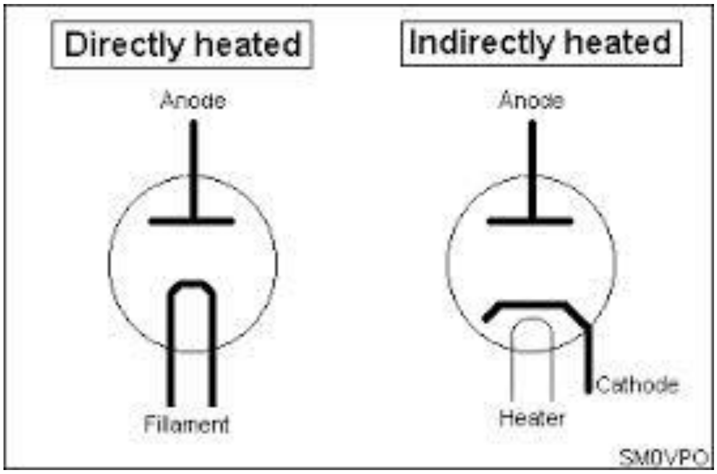


The electrons flowing between the cathode and the anode form a cloud which is known as the "space charge". It can tend to repel electrons leaving the cathode, but if the potential applied to the anode is sufficiently high then it will be overcome, and electrons will flow toward the anode. In this way the circuit is completed and current flows.

As the potential is increased on the anode, so the current increases until a point is reached where the space change is completely neutralised and the maximum emission from the cathode is reached. At this point the emission can only be increased by increasing the cathode temperature to increase the energy of the electrons and allow further electrons to leave the cathode.

If the anode potential is reversed, and made negative with respect to the cathode it will repel the electrons. No electrons will be emitted from the anode as it is not hot, and no current flows. This means that current can only flow in one direction. In other words the device only allows current in one direction, blocking it in the other. In view of this effect, the inventor of the diode vacuum tube, Professor Sir Ambrose Fleming called it an "oscillation valve" in view of its one way action.

The Diode



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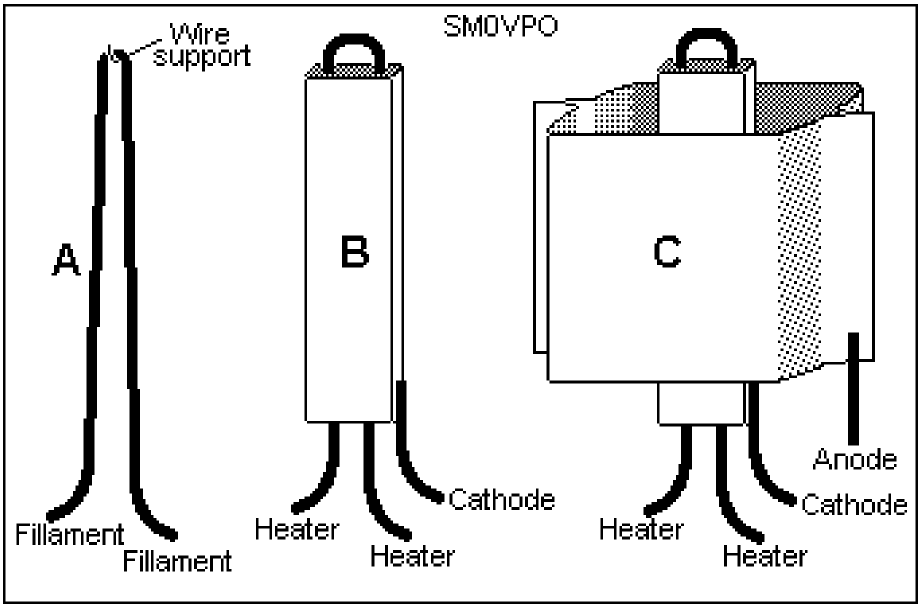
Basically, when an electrode (CATHODE) is placed in a vacuum, coated with Barium Oxide and heated to several hundred degrees, the electrons on its surface become more agitated and form a cloud around the cathode's surface. From this cloud of electrons it is easy to attract electrons to a positively charged electrode (ANODE). The anode only needs to be placed in the same vacuum as the cathode. Electrons will flow from the heated cathode to the relatively cool anode, but electrons will NOT flow from the anode to the cathode because there is no Barium Oxide coating on the anode and it is too cold. We have formed a DIODE valve. Here are the circuit symbols.

DIRECTLY HEATED
The cathode is a bit of filament wire coated with Barium Oxide and a current is passed through it to make it get hot. One of the two filament terminals is used as the cathode connection. This method of heating a valve cathode was most often used in battery portable equipment and HT rectifier valves. The filament voltage is normally 1.4 volts for battery valves such as 1T4, 1L4, 1S4, DF91, DL91 etc. Directly heated HT rectifier valves commonly used 5 volts to heat them. Early valves used only 2.5 volts for the filament.

A huge disadvantage of a directly heated diode is that current flowing from cathode to anode is added to the filament current. If this current becomes too large then the filament can become too hot and burn out, just like an overloaded torch-bulb.

INDIRECTLY HEATED
The non-coated filament wire is inserted into a Barium Oxide coated metal tube and insulated from it. The filament is only used to heat the cathode tube and so it is normally called the HEATER.



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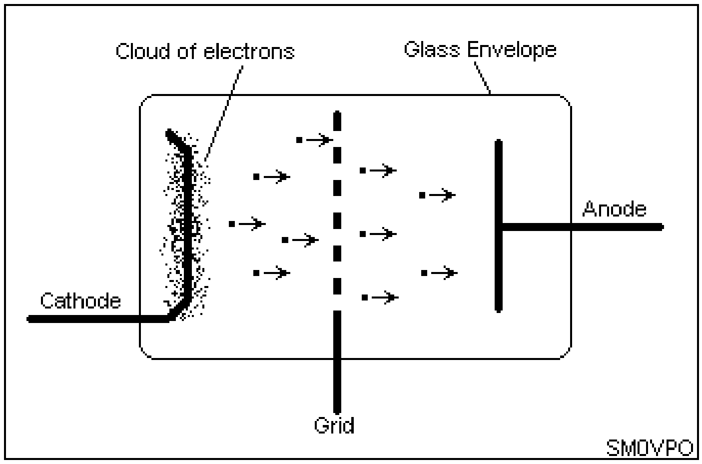
The Triode



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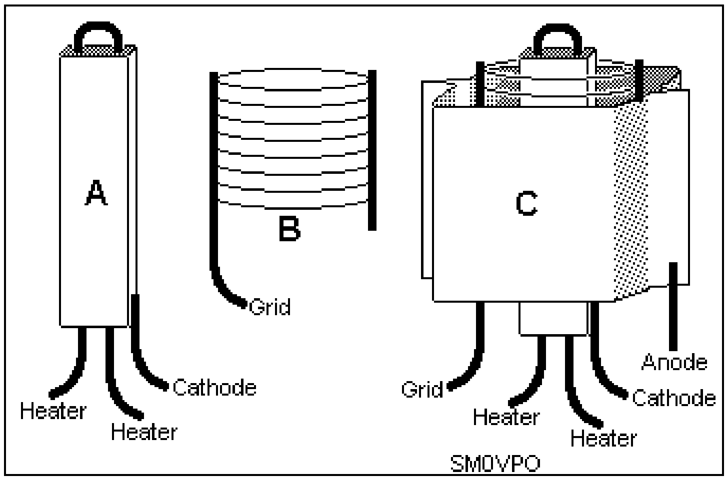
To make an amplifying device (and to prevent the catastrophic scenario above) we need to regulate the current flowing from the cathode to the anode of a valve. If we insert a wire mesh or GRID between the anode and the cathode we can control the electron flow and so we have created a TRIODE:

This grid is called the CONTROL GRID. With a few hundred volts positive on the ANODE and the negative on the cathode, electrons from the electron cloud around the heated cathode will go coursing their way towards the anode. But the wire mesh/grid is in the way, no problem; they just go through the holes. But if we connect a small negative voltage to the grid (with respect to the cathode) then the wires of the grid will have a field around them that will repel electrons. This field of repulsion will effectively reduce the size of the hole the electrons can pass through, thereby reducing electron flow and the anode current. If the negative voltage on the grid is made even more negative then the field of repulsion around each grid wire can become so wide that they all join up. This will cut the valve off totally and NO electrons can flow from cathode to anode.

The Triode



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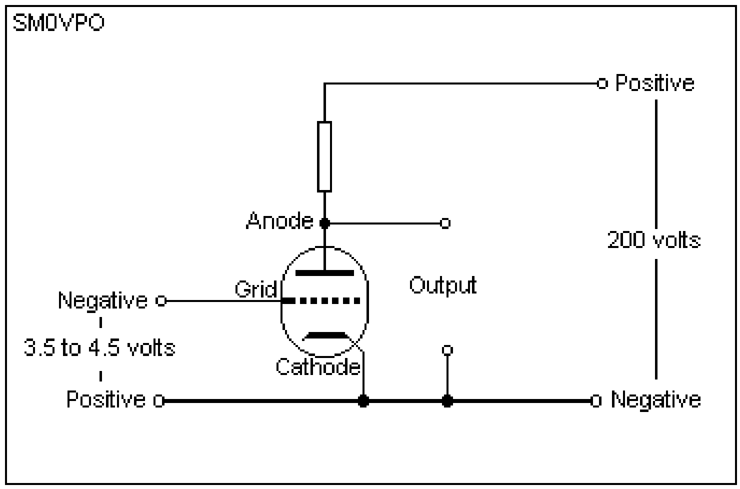
Here is the typical construction of a triode valve. The same cathode (A) is used as for a diode, but a grid (B) is placed around it. The grid is commonly composed of two vertical lengths of wire about 1-2mm Diameter spaced about 1 cm apart. Between these two wires a very thin 'hair-like' wire is wrapped around loosely so that it forms a circular or oval cylinder. The grid wires are spot-welded to the two vertical wires.

Using the Triode



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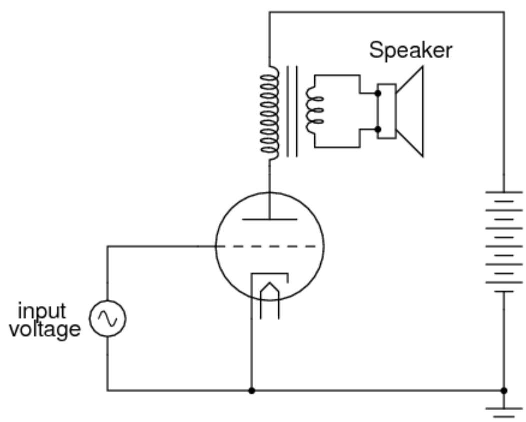
A typical triode valve will control an anode current by means of varying the voltage on the valve's grid. Typically, the anode will be 2mA (0.002 Amperes) for a grid voltage of 4 volts NEGATIVE (with respect to cathode). If we vary the grid voltage from -3.5 to -4.5 volts the anode current will vary, typically, from 1mA to 3mA.

By varying the grid by 1 volt (-3.5v to -4.5v) the anode current changed from 1mA to 3mA. The CHANGE is 2mA. The 2mA change will give us a 100 volt change across the anode load resistor. One volt signal in = 100 volts of signal out. Voltage amplification factor is therefore 100, and this figure is quite typical for a valve.

Note that there is no current flowing to or from the grid under normal conditions. The grid input impedance is therefore not far from infinity.

Triode Audio Amplifier



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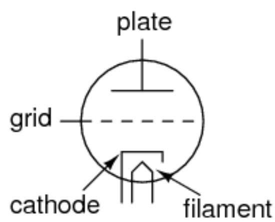
Grid Bias

- If we make the grid sufficiently negative, all electrons will be repelled, and none will get through to the Anode.
- This is called cut-off.
- That voltage value is called the cut-off bias.



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Comparison – Transistors and Tubes

	Transistor	FET	Triode
Input	Emitter	Source	Cathode
Output	Collector	Drain	Plate/Anode
Control	Base	Gate	Control Grid

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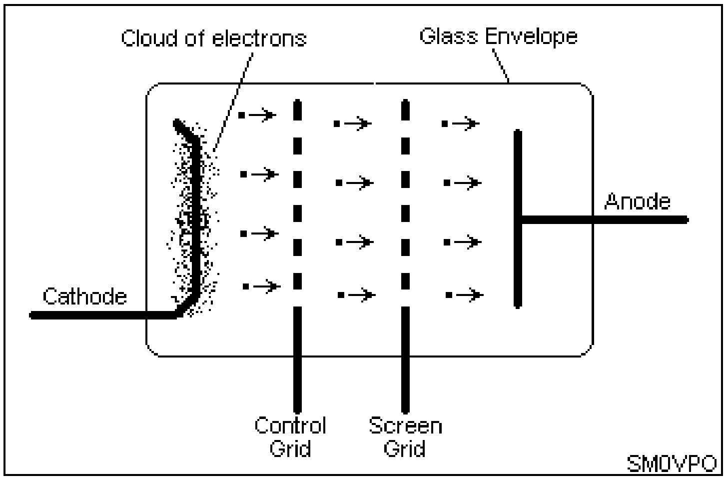
The Tetrode



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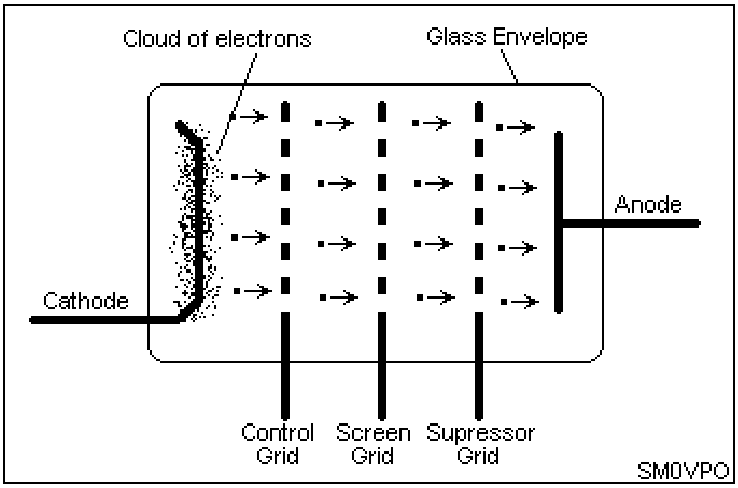
One of the biggest problems with the triode valve is the small current it will handle. Anode currents of a couple of milli-amperes are of little use for powers above about half a watt. For radio frequency use, the capacitance between the anode and the control grid of a valve can become a problem by providing unwanted feedback. Earlier triode valves used anodes or grids mounted at the top of the glass bulb as an attempt to get the connections as far away from the others as possible.

Another solution was to insert a second grid between the control grid and the anode. This additional grid was called a SCREEN GRID and a valve with two grids is called a TETRODE.

The valve may still be used exactly as a triode, but a few hundred positive volts are applied to the screen grid, usually about 66% of the anode voltage. Electrons whizzing past the negative control grid are retarded, but immediately after the control grid lies a few hundred positive volts on the screen grid, so the electrons continue their journey with renewed vigour. As they get to the screen grid they will feel the influence of the anode with its higher potential and so the majority will head for that.

When the electrons flying through a tetrode hit the anode they can knock electrons off the anode plate due to the impact. Most of these 'liberated' electrons become attracted back to the anode. Some, however, are happy with their freedom and fall under the influence of the screen grid. This is called SECONDARY EMISSION. Secondary emission gives the tetrode characteristic curve a very peculiar non-linear 'kink'.

The Pentode



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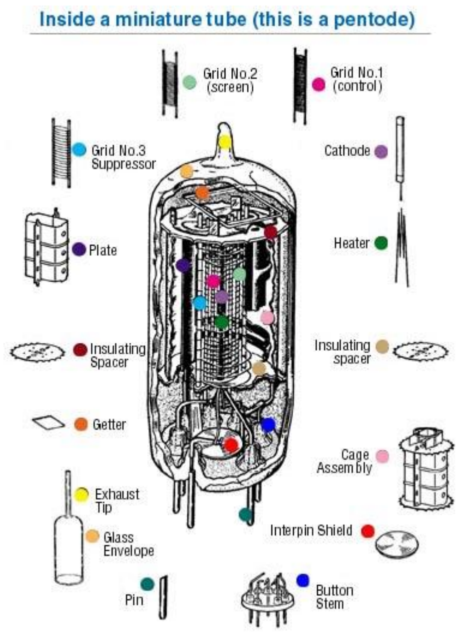
The solution to the 'kinky' tetrode is the PENTODE, which has yet another grid, the SUPRESSOR GRID (G3). The suppressor grid is normally held at cathode potential so any electrons liberated from the anode are shielded from the screen grid. This way they only feel the attractive force of the positively charges anode, so they go back to the anode where they belong.



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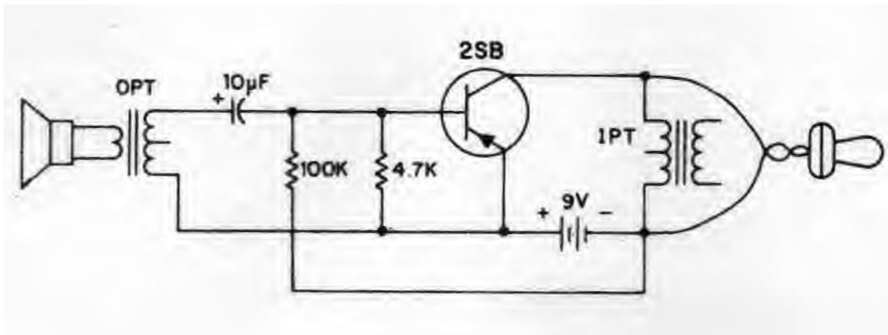
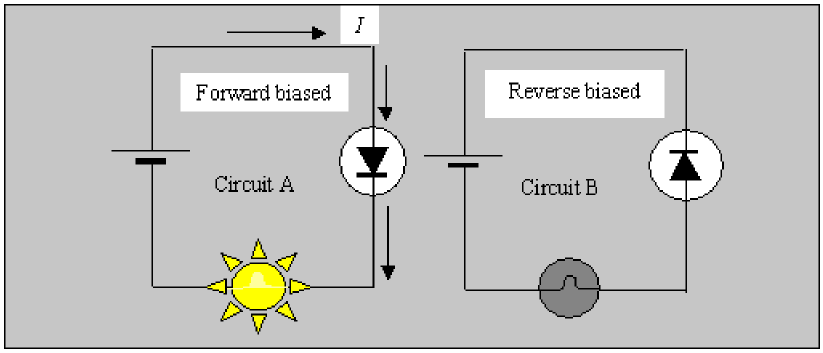
Simple Audio Amplifier





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•In circuit A the diode is **forward-biased** so the current flows and the bulb will light.

•In circuit B the diode is **reverse-biased**, the current will not flow and the bulb will not light

Current Flow

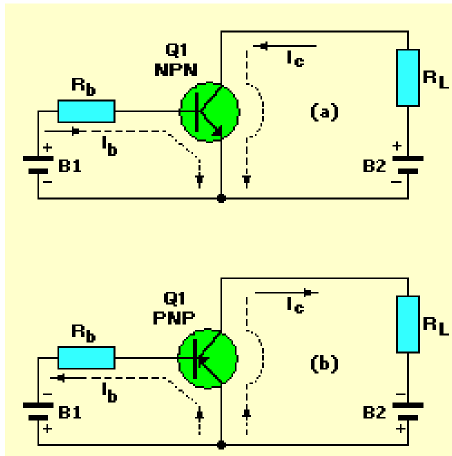

Fig. 3--CURRENT FLOW in transistors: NPN (a), and PNP (b).

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